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The Effects of Harmonics on Power Quality and Energy Efficiency

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The Effects of Harmonics on Power Quality and Energy Efficiency

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Glossary of Terms

DC Power (Direct Current) – Power delivered by a current that flows in only one direction from source to load.

Displacement Power Factor, The ratio of real to apparent power for an inductive or capacitive linear load. (Displacement Power Factor = kilowatts / kilovolt amps, for an inductive load the current lags the voltage and the power factor is called “lagging.” For a capacitive load the current leads the voltage and the power factor is called leading. In all cases if the current and voltage are in phase, the displacement power factor is unity (1). Displacement power factor ranges from unity to zero. The value of displacement power factor is also given by the cosine of the angle by which the current lags or leads the voltage

Flicker – Perceived dimming (pulsing) of lights, usually due to rapid small changes in voltage on a distribution system. Flicker is also the term used for intermittent light dimming. EG: a large load goes on, the voltage sags for the duration of that load operation, and the lights dim, then brighten again when the load goes off. While not physically harmful to personnel, flicker can be very annoying. Due to the fact that the human eye can easily detect very small changes in light level, flicker is of great concern to the power quality industry.

FOURIER ANALYSIS – A method of mathematically breaking a non-sinusoidal waveform into harmonic components so that the sum of these components represents the original waveform. This method was first published by John Baptiste Joseph Fourier in 1823.

Introduction

Most of the world's population is reliant upon electrical energy and all are affected by the production of carbons as a result of generating electrical energy, unless it is produced by renewable source. The biggest challenge ever to the world is upon us in relation to energy production, it is of paramount importance for the future of mankind that we plan and understand the consequences of what we are doing and will do, so that we can live in harmony within our fragile world. There are a number of factors which have led to the position we find ourselves in. Natural resources such as oil and gas are running out as we reach peak fuel exploration and consequently fuel production. This is driven by the combination of an ever increasing world population coupled with the increased usage and greater reliability on electrical products such as combustion engines and personal climate control, such as air conditioning and central heating. Inevitably energy costs will greatly increase and this alone is a good reason for energy conservation and efficacy.

Climate change, due to the effect of green house gases being discharged into our atmosphere, is causing problems such as: crop failure; the starvation of millions; melting of the ice caps and resultant flooding, to mention but a few. So how does the subject of harmonics come into electrical energy conservation and what can this research do to help improve the atrocious situation we find ourselves in? The European community has committed to reducing our carbon emissions by signing up to the Kyoto protocol, also further agreements are expected that will supersede Kyoto. The ways in which we will do this in relation to harmonics are to improve electrical energy efficiency by reducing the waste of electrical energy. By making our electricity supply more secure, reliable and versatile means that we will reduce reliance upon the major oil and gas fuels, which mostly exist outside of Ireland and the European community. The majority of our fuel is imported and this makes our economy dependent on outside interests, out of our control, even more so as world fossil fuel reserves are running out and demand is increasing. If we make our energy networks secure and designed to the highest standards we can import and export energy more easily as our demands change, for example by exporting to other European countries any surplus energy from for example wind farms or wave energy. This is achieved by paralleling all our power stations and micro electricity plants, i.e. combined heat and power plants, wind turbines, hydro power, wave power and photovoltaic installations. These plants connected to the grid system must be reliable, producing power of premium quality. The risk of faults occurring must be minimised and contained as certain faults can cause overloads that can trip out vast electrical distribution networks. It is envisaged that with ever increasing climate change more sudden demands will be put on our electricity networks, for example the increase in summer heat waves in the late nineties and early 21st century which caused black outs in many major cities of the world. So how do harmonics make our electricity supplies more vulnerable? One way is by achieving a good standard of power quality. This is controlled by both the producer and the consumer. Harmonics create further losses in distribution networks and within the consumer's installation. They also reduce the life expectancy of electrical machines such as transformers and motors causing overloads on cables and nuisance tripping on circuit breakers.

These issues affect our electricity distribution system and can lead our electrical energy system to fail, thus reducing our security of supply. To further this, the greater demands and the more non linear equipment we use means harmonics will be ever increasing. Nowadays almost all electrical loads, with the exception of filament lamps or a resistive heating load, cause harmonics.

Literature Review

In order to solve this problem we turn to mathematics, specifically, Fourier analysis. Simply stated, using Fourier analysis we can prove: Any periodic waveform can be expressed as a series of sine waves with varying frequencies and amplitudes. It is important to remember these harmonics are simply a mathematical model. The pulses, square waves, or other distorted waveforms are what we actually see if we were to put an oscilloscope on a building's wiring systems (Copper Org., 2009).

Harmonics can cause a number of problems for both the electricity consumer and the electrical supply companies some of which are:

- Causing greater cable losses in all power distribution cables resulting in poorer energy efficiency
- Non cancellation of triple-N currents resulting in larger neutral currents than phase currents
- Operation of circuit breakers and fuses causing power failures
- Circulating currents in the windings of distribution transformers, reducing the age, reliability and efficiency of the transformer
- Operation of sensitive electronic equipment such as computers causing them to lock-up, crash and malfunction.
- Further reduction of power factor and the effects that is inherent to that.

So what are the costs for poor power quality and associated Harmonics? "It is estimated that power quality problems cost industry and commerce in the EU about 10 billion per annum while expenditure on preventative measures is less than 5 % of this." (Chapman, 2001). "Publications lead to a global bill for poor power quality of €500 billion euro per year, i.e. 50% of the turnover of the global electricity sector. For many business uses, the cost of poor power quality is higher than their electricity bill." (Keulenae, 2003) "Except for some basic fundamental work, the cost impact of harmonics is not yet well understood, but a recent Eurelectric report estimates it at several €100 billions of Euro per year globally" (Eurelectric, 2002). To compensate for these harmonic losses more power must be generated, reducing the life of electrical equipment, thereby increasing the size of cables and transformers. Basically harmonics have no advantages and all the disadvantages. It is envisaged that ultimately it will be the case that consumer equipment that produce harmonics will be penalised financially for the effects on our distribution system and the losses they create.

As stated earlier the European Union estimates that poor power quality costs hundreds of billions of euro each year and yet we only invest €50 billion (Eurelectric, 2002) in an effort to improve the problem.

The additional losses that occur in wiring installations due to harmonics are referred to as joule losses (I^2R). When current flows in a conductor, losses occur due to the resistance, i.e. resistivity of the cable. These losses are proportional to the square of the current, multiplied by the resistance of the wiring. Due to harmonic currents the losses in the conductors are increased above the level of the 50Hz current. As stated as a result of the harmonic loads, this increases the losses in the electrical distribution network by 2-3% of the load (Chapman, 2001). Also consideration must be made for the cost of the fuel and reliance on the importation of the fuel, all which affects our gross domestic product (GDP). We will also find ourselves in a vulnerable position as other countries, more powerful than ours, will demand and have greater control of the world's fuel. Recent global unrest has only just brought this to our attention. It is time we provide a sustainable and efficient electrical distribution system. It is also the case that these harmonic losses will increase each time they are transformed by power distribution transformers within our installation and within the National Grid system, further adding to our losses. Harmonics cause losses within the core itself. In addition, the harmonic currents circulating within the transformers windings cause premature aging, resulting in the life expectancy of the transformer being reduced, incurring the cost of replacement and further risk to the security of supply being compromised if the transformer was to fail before its planed replacement. Further problems subsequently result from the inconvenience and power outage while replacing the transformer before its normal retiring lifetime. Another method of reducing the effect of cable losses and transformer losses due to harmonics is to upsize the cables and plant. Once again however this incurs energy to produce and mine for copper and metals to manufacture these materials. All of the above have an ever increasing demand on our world resources and the security of our modern way of living. By ensuring the efficiency of our electrical network and by having a true understanding of our loads and the way in which we do everyday activities, will assist us in ensuring a better and more sustainable future for us all

Chapman asks how much should be spent on power quality prevention and states that this is the individual assessment of the power interruptions potential. However, a full understanding of the problem must be appreciated. It is easy for us to relate to Chapman, as will be evident in the laboratory measurements. The causes of harmonic distortion are all non-linear loads such as compact fluorescent lighting, discharge lighting, personnel computers, televisions, variable speed drives for motors, arc furnaces and all other electronic equipment that is being supplied from switch mode power. It is also evident that the measurement of harmonics cannot be achieved by using low cost instruments. It is necessary to use true Root Means Square (RMS) instruments, as the normal available average RMS type instrument can result in an underestimation of up to 40%.

As Chapman reports, harmonics increase losses, thereby increasing temperatures in the transformer. To avoid many of the problems caused by harmonics is down to good electrical installation practice and proper equipment selection, for example by upsizing cables to reduce I^2R Joule losses. Another paper by Chapman, relates to the cause and effects of harmonics and states "Harmonic frequencies are integral multiples of the fundamental supply" (Chapman, 2001) i.e. 50 Hertz therefore the third harmonic is 150 Hertz and the fifth harmonic is 250 Hertz. Also stated is that harmonic currents and the origins are of great concern. These harmonics are greatly increased due to the ever increasing use of electrical equipment demanding a non-linear load. Take for example a typical modern day office environment in comparison with an office 20 years ago. Today's office now contains a multitude of electrical equipment, to name just a few: a personnel computer, visual display unit and printer; fluorescent light fittings; digital telephone extension; mobile phone charger. All consisting of switch mode power supply units and all creating harmonics. A common method of quantifying harmonics is in percentage terms i.e. 35% Total Harmonic Distortion (THD), this is used in most reference material and standards worldwide. There is also a range of International Electrotechnical Commission (IEC) standards relating to different areas of harmonics and for the purpose of this study below is a list:

Harmonic Standards

- IEC 61000-3-2 (International Electrotechnical Commission, 2007) which specifies limits for harmonic current emissions applicable to electrical and electronic equipment having an input current up to and including16A per phase, and intended for connection to public low-voltage distribution systems.

- IEC 61000-3-4 (International Electrotechnical Commission, 2007) which specifies limits for harmonic current emissions applicable to electrical and electronic equipment having an input current greater than 16A per phase, and intended for connection to public low voltage distribution systems. This document is a technical report.
- IEC 61000-3-12 (International Electrotechnical Commission, 2007) the recommendations of this are at present a draft standard and are applicable to electrical and electronic equipment with a rated input current exceeding 16 A, up to 75 A per phase and intended for connection to public low-voltage AC distribution systems.
- IEEE 519 (International Electrotechnical Commission, 2007) establishes limits on harmonic currents and voltages at the point of common coupling (PCC) or at the point of metering.
- IEC 61000-4-13 (International Electrotechnical Commission, 2007) which proposes different immunity levels in accordance with different performance criteria.
- IEC 61000-3-6 (International Electrotechnical Commission, 2007) establishes planning levels for MV, HV and EHV networks as well as the conditions for connecting disturbing loads producing harmonics.

Harmonic Data Analysis

The majority of electrical devices and appliances which cause harmonics and this will be referred to in later chapters, namely switch mode power supplies used for the majority of power supplies on personal computers, televisions, and all electronic equipment. Traditionally power supply units have used wire wound transformers and bridge rectifiers. However, due to the size, cost and weight, manufacturers now use directly controlled rectification of the supply to produce a direct current which draws a pulse of current as opposed to a continuous current which in return creates large amounts of third and higher harmonic currents. Depending on the type of load the harmonic current mostly increasing is the 5th Harmonic, as per Eurelectric publication (Eurelectric, 2002). Figures 1 to 2 are taken from the Eurelectic report that are an association representing the common interests of the European Electricity Industry and has worldwide affiliates and associates.

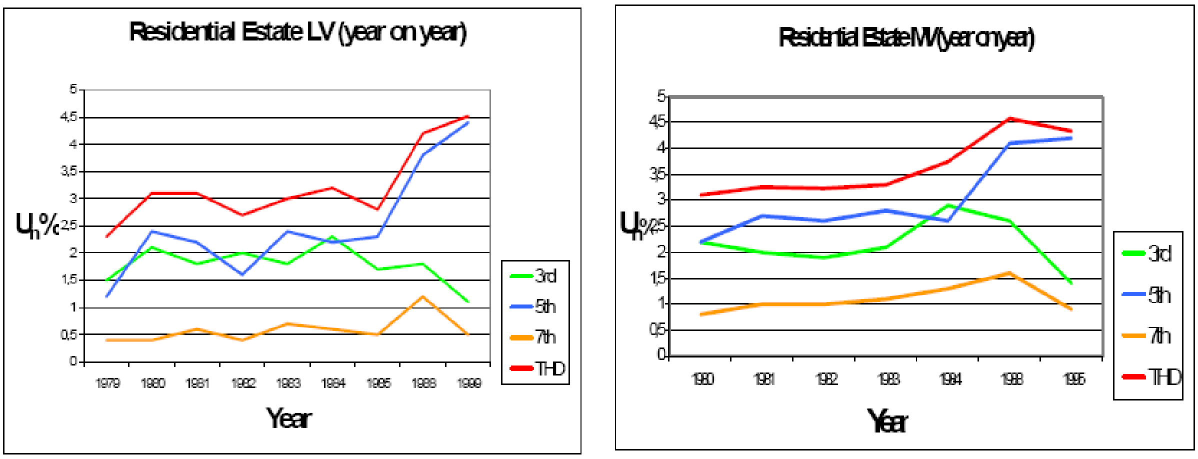
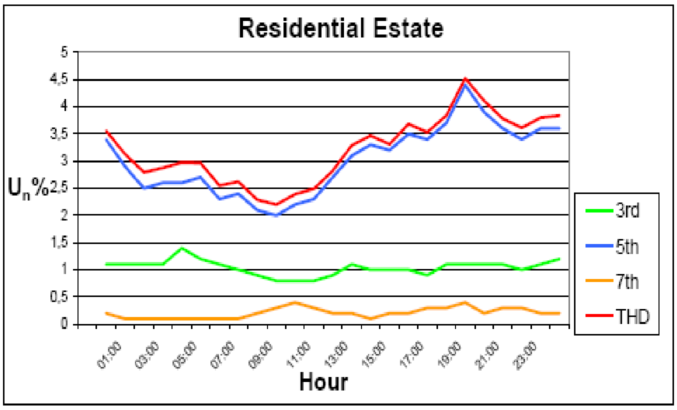


Figure 1. Harmonic monitoring for residential and industrial supplies (Eurelectric, 2002)



Comment: The 5th harmonic is the dominant one and follows the typical daily load pattern. It has its peak of 4.4 % at 7 pm (THD = 4.52 %). There is no coincident rise in the 3rd and the 7th harmonics, indicating that the source of the rise in the 5th harmonic might be on an adjacent section of the network. The most likely cause for the rise in the 5th harmonic would be TV load.

Figure 2. Harmonic monitoring for a UK residential estate. (Eurelectric, 2002)

The next area to be looked at is compact fluorescent lamps, which contain electronic ballast. Again many reports that these devices are producing harmonics and are increasing in use and has found them to be problematic. This is particularly evident today in hotels where they have moved over from traditional filament type lamps.

Creation of Harmonics

Theory on how harmonics are generated is as follows: In an ideal clean power supply system, the current and voltage are purely sinusoidal. In practice non-sinusoidal current results when the current flowing in the load is non-linear, related to the applied voltage. An example is given when a full wave rectifier current only flows when the charge on the capacitor reaches a certain value of the supply voltage i.e. close to the peak voltage. The equivalent circuit of a non-linear load is a good explanation of a typical circuit where the load creates a number of harmonic currents which in return flow around supply systems impedance and clearly explains the importance of quantifying these harmonics. These currents must be measured by means of analysing them. In a very similar way results will be measured and analysed using a Fluke 43B Power Quality Analyser. With the explanation of how harmonics are generated we can look at the problems they cause.

Effects on the Neutral Conductor

One of the issues is that of neutral conductors overheating. According to Chapman this occurs because under linear load conditions, when each phase of a three phase system carries the same value of current, the resultant return current will equal zero as they cancel each other out. When a non-linear load is being supplied by a three phase system, again the fundamental current cancels out but the triple N harmonic currents do not cancel out. Chapman states the odd multiple of three times the fundamental, the triple N harmonic currents actually add to the neutral as shown below in Figure 3.

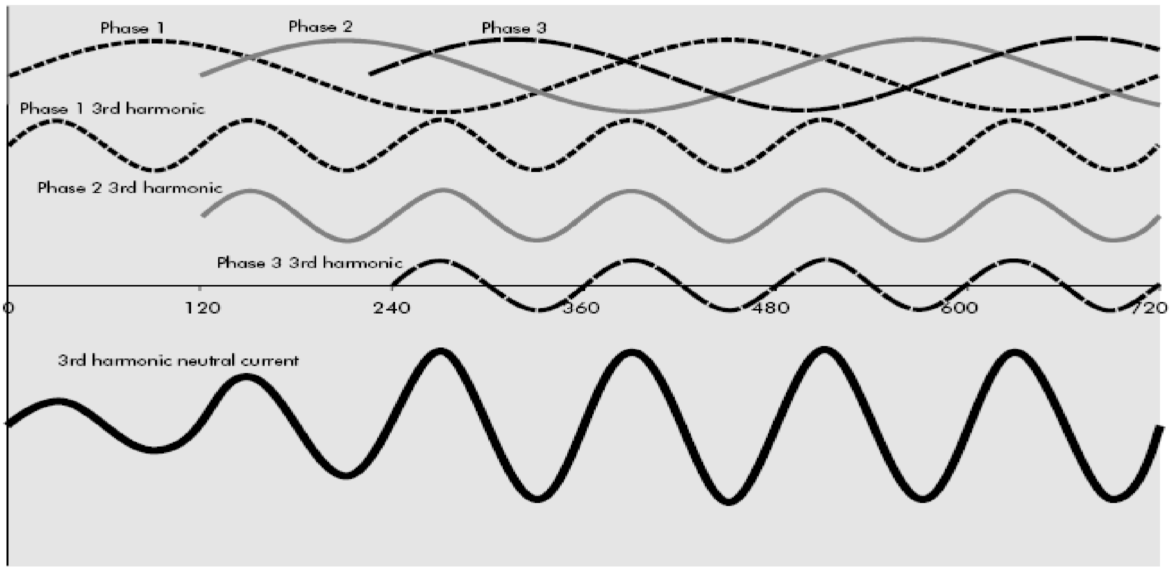


Figure 3. Triple –N currents add in the neutral conductor. (Chapman D. 2001)

The triple N harmonics currents are the third, ninth, fifteenth (any order divisible by 3). If the third harmonic current is 70% for each phase, the neutral current will be 210% times the phase current. In tests carried out in commercial buildings it was found that neutral conductors are carrying between 150% and 210% of the phase currents. Tests that will be conducted to conclude this will be by measuring the current of a particular building as an example. At present, the correction for overcoming this problem is to de-rate the cables that are supplying large harmonic loads or by upsizing the cable as per IEC Standard 60364-5-52 (International Electrotechnical Commission, 2007). “The simplest way to solve the problem is to apply appropriate corrective coefficients to the cable current carrying capacity”. Annex D of IEC Standard 60364-5-52 also gives a methodology for determining the appropriate re-rating factor.” (Desmet, 2003). Table 1 below gives the reduction factors to be applied to cables containing the third harmonic currents.

3rd harmonic line current (%)	Value selected on the basis of the **line** current	Value selected on the basis of the **neutral** current
0-15	1.00	-
15-33	0.86	-
33-45	-	0.86
> 45	-	1.00

Table 1. Reduction factors for cables carrying triple-N currents (International Electrotechnical Commission, 2007)

This IEC standard from Table 1 is used so that the cable is not overloaded by its current carrying capacity and therefore will dissipate the heat generated by the current flowing in the phase and neutral conductors. In the paper neutral sizing in harmonic rich installations Baggin & Desmet concluded that it is necessary to apply the IEC standards (Baggin&Desmet, 2003). Again, relating to the current carrying capacity of the cable and the amount of heat that can be dissipated is a factor of its current carrying capacity, and in relation to the triple N harmonic currents as they do not cancel out like in the vector sum of the three phase currents supplying a linear load.

Also referencing to the IEC standard 60364 which states that the neutral conductor must be at least the same size as the phase conductor for single phase and multi-phase circuits. However according to clause 542-3 where reduced cross-sectional cables are used, providing that the maximum current including harmonic currents does not exceed the current carrying capacity of the neutral conductor, or that the neutral has to be protected by an over current device, but the minimum size of the conductor has to be 16mm squared copper or 25mm squared aluminium. To enable this, extensive knowledge of the installation is necessary. This is difficult in a new installation. However it is stated Desmet&Beggin that it is not possible to determine the neutral current in absolute terms unless the real or theoretical waveform of the current is known. Typical guides of approximation of the neutral current can be 1.61 times the phase current for loads such as computers and 1.73 times for controlled rectifiers. Again according to IEC Standard 60364 Table 1 above is recommended depending on the percentage of the triple N quantity of harmonic currents. The table shows that if up to 15% triple N harmonics exist in the phase current no increase in the neutral is generally required. However, the increase of 6% heat generation will exist. For harmonic levels of between 15% and 33% an increase in cable size by a factor of 0.86 is necessary. When the triple N harmonic current exceeds 33% up to 45% the cable size is determined by the neutral current and de-rated by 0.86.

ETCI National Rules

The Fourth Edition of the Irish National Wiring Rules ET101 2009 has existing and implemented updated guidelines for consideration for harmonic currents. Here are some brief descriptions of same:

- 431.2.3 Requiring overload protection on the neutral conductor.
- 524.4.1 States that the neutral conductor must equal the size of the phase conductors.
- 524.4.2 States that if harmonic current is greater than 33%, the neutral conductor is to be increased in size by 1.45 times the design current (ECTI, 2009).

Another additional cable loss is due to what is referred to as "the skin effect", this occurs in the phase conductors and it is a small loss at 50Hz but starts to play a role from the 7th harmonic 750Hz and upwards. "For example, a conductor with 20 mm diameter has 60% more apparent resistance at 350 Hz than its DC resistance. The increased resistance, and even more the increased reactance (due to higher frequency), will result in an increased voltage drop and an increased voltage distortion (Keulenaer, 2002)."

Losses and Effects in Transformers

The next consideration on harmonic current effects is the transformer, where there are two factors where harmonics effect transformers, these are the losses that normally occur at 10% of the load on the full load, this doubles the losses to 20% when the transformer is supplying a non linear load comprising of, for example computer equipment or other harmonic generating equipment. Losses in transformers are due to stray magnetic losses in the core, and eddy current and resistive losses in the windings. Of these, eddy current losses are of most concern when harmonics are present, because they increase approximately with the square of the frequency (Chapman D. 2001). The overall results are higher operating temperatures which result in a shorter life for the transformer. The second, is the triple N harmonics circulating in the windings of the transformer and this must be considered when rating the size of the transformer, the transformer should have a suitable K rating. This is a factor to allow for harmonic loads. A paper Desmet & Delaere on the selection and rating of transformers (J. Desmet, 2009) supported Chapman's paper and states that the increase of non-linear loads is continuing to grow rapidly. The harmonic currents increase the transformation losses resulting in the increase of the transformers temperature, thus reducing its life expectancy. Desmet, Delaere & Lemcko states that when specifying a transformer a K-rating of the transformers capacity or other methods of deriving a K Factor is recommended. Also, the modern transformer has wire foil type windings and usually continuously transposed conductors (a form of overlapping and laminating conductors) this assists in reducing these harmonic losses (Desmet D. &., 2009).

Nuisance Power Failure and Good Circuit Design

The next issue associated with harmonics and power quality is the importance and understanding of accurate measurement of current that flows within the circuit. Baggini's paper states power failure can result in nuisance tripping of circuit breakers or blowing of fuses, due to the non-consideration of harmonics. Also socket outlets are protected by residual current circuit breakers, these devices measure the phase and neutral current and if an imbalance occurs they operate by disconnecting both poles of the circuit. They usually operate with an imbalance of 30 milliamps or greater.

These devices are relatively simple devices and may not be able to sum the higher harmonic frequencies resulting in nuisance tripping of residual current circuit breakers. Another issue with residual current circuit breakers due to harmonics is switching noise caused by the typical switch mode power supplies and other electronic switching devices which cause harmonics. The switching noise must be filtered out and this is achieved by connecting a capacitor between live and neutral and earth. This filter leaks a small current of approximately 3.5 Milliamps. If a large amount of equipment is on one circuit then the operating threshold of the residual current circuit breakers (RCCB) value can be exceeded and operate unnecessarily due to poor circuit design (Baggini, 2007), the RCCB detects the imbalance due to the noise filter leakage current, resulting in the tripping of the residual current circuit breaker giving rise to a power failure. One way to overcome this problem is to spread the load over a number of socket circuits within an installation.

True Measurement

As earlier mentioned another major cause of power disruption is where the true RMS current that exists within the circuit is not measured correctly, thus resulting in an undersized circuit breaker or fuse being installed. This is mainly caused by higher harmonic currents rather than at the fundamental 50 Hz current i.e. the harmonic current that is not expected or accurately measured in the circuit. A more specialised paper that supports Chapman's paper is by Ken West (West, 2001) which states that an inaccuracy of up to 40% of underestimated current can flow in a circuit which contains harmonic currents feeding non-linear loads. It is required to understand how current measuring instruments work and the sinusoidal waveform when a non-linear load is being supplied by a number of currents exist within the circuit the fundamental current at 50 hertz and a number of harmonic currents i.e. the third harmonic at 150 hertz and so on. These currents add to each other resulting in a far from perfect sine wave as shown below in Figure 4.

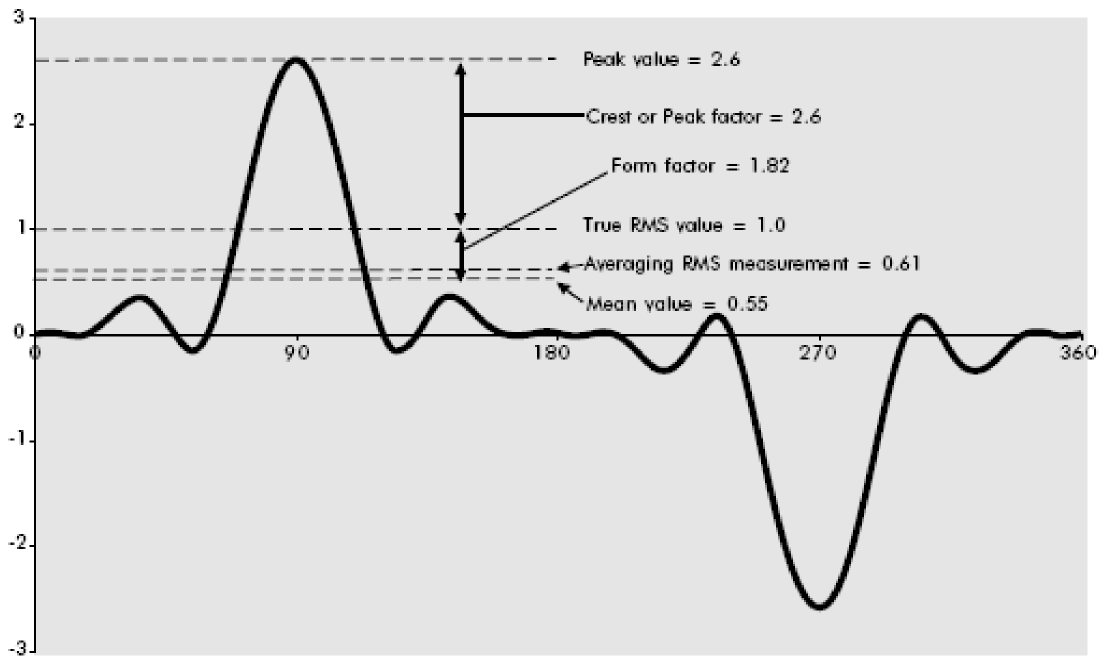


Figure 4. Typical distorted current waveform for a PC showing mathematical values (West, 2001)

Figure 4 shows a typical waveform from a personal computer. The only method to measure the current accurately is by means of using a true RMS meter, as opposed to using a lower cost and more widely average reading RMS meters. Average RMS meters measure the peak of the sine wave and multiply it by 0.707 thereby giving the average RMS reading. However, this is only accurate for a pure sine wave. This is due to the majority of loads now being non-linear in nature and having a resulting waveform not close to the pure sine wave where the peak value can vary in excess and the average value being much lower. West states that the instrument to measure current that measures the whole and accurate value is the true RMS meter. This takes the square of the instantaneous value of current over time. However, its limitations are measurements of up to the 50th harmonic and having a crest factor of at least three. The crest factor is the ratio between the true RMS value and the peak value of the waveform. It is also noted by West that the inaccuracy between the two instruments can be up to 40% underestimation from the average RMS reading. This percentage underestimation is dependent on the current waveform type. This will be further investigated in laboratory measurements where there are available numerous types of average RMS amp meters and true RMS meters.

Methodology

In order for measurements to be accurate, and the result to be appropriate and reliable, an appropriate power quality harmonic analyser must be selected. That which was used on the Leonardo Energy reports was a Fluke Power Quality Analyser Instrument and the model to be used for the purposes of this study is a Fluke Power Quality Analyser 43B which fully conforms for lab and on site measurements and calibration dated November 2009 as published by the BISRA Power Quality Advice Guide 2/2000 (Pearson, 2000) and from previous experience of circuit analysis we are required to consider the following for on site and lab measurements:

1. Health and Safety
2. Instrument Selection
3. Point Location of Measurement
4. Point of Common Coupling
5. Measurement Methods
6. Problems
7. Calculation and Assimilation Methods
8. Assumptions for Harmonic Studies i.e. background harmonics.
9. Consideration of time varying characteristics of harmonics.

Health and Safety

When working and connecting instruments the electricity supply must be de-energised. There should be no exposed conductive parts and circuits must be protected by residual circuit breakers. Risk assessment needs to be continuous in order to prevent electrocution or injury. The power quality instrument must be suitable to measure harmonics up to the 50^{th} harmonic as standard practice and in this case it would be desirable to download measurements onto a personal computer for analysis, taking various measurements of voltages, currents, frequency, true RMS current measurement, power, power factor, total harmonic distortion. The instruments should be accurate and should be useful for determining compliance with the standards or regulations. For onsite analyses for the building electricity supply, it is recommended to measure at the point of common coupling. This point can be on the high voltage side of the supply transformer or the low voltage side.

In this case the supply authority feeds a number of consumers from the one transformer and there was no access to the common point where the supply and other utility customers are connected, therefore the main distribution board is the closest point to the point of common coupling which is satisfactory. Results will be a snapshot of the type of load that exists on the installation. The measurements can only be taken after hours for a brief period of time and the saved data should ideally include:

- RMS Values
- Frequency
- Total harmonic distortion
- Total harmonic distortion – Fundamental Harmonic RMS
- Voltage and Current Waveforms
- Harmonic Current Waveform

From direct current to the 50th harmonic, bar charts are very useful methods to compare the harmonic levels and their relationship. In this particular study it would be desirable to take measurements over a period of time, say one day/one week intervals as a more accurate picture can be seen or over a period of production time. These histograms are a good way to evaluate power quality problems as they are compiled over a long period of time and indicate the different loads that exist.

Measurements that aid in Understanding Harmonics and Power Quality

The first measurement of harmonics considered will be to measure the power quality parameters in Kevin Street College, Church Lane which consists of offices, workshops, laboratories and class rooms. The lighting consists of fluorescent fittings with iron-core ballasts installed approximately 20 years ago. A very small amount of induction motors are in use. The heating is provided by means of an oil burning boiler. There is a considerable amount of information technology equipment located in offices and laboratories. This mainly consists of approximately sixty personal computers with flat screen monitors and their associated power supply units. The water heating is by means of electric storage. The building is usually occupied for 12 hours per day, five days a week, during term times. It has a 400 volt three phase and neutral supply, fed from a shared 10KV transformer supplied from the national grid.

With the aid of the Fluke 43B Power Quality analyser, the various harmonic currents in the phase and the neutral conductors can be measured. The results will be shown on subsequent figures for analysing. It is hoped by this that it can be demonstrated that the load contains considerable harmonic currents. Many different types of loads will exist, for example water heating will be a linear load as it is purely a resistive load and the results of certain complex waveforms where the sum of harmonic currents will cancel each other out. The different levels will vary over the period of the day as this is dependent upon the occupancy of the building. For example when a laboratory class is in session and instruction is taking place, the personnel computer based programmable logic controllers with the non linear load will increase, consequently programmable logic controllers often result in malfunction due to harmonics.

When we consider a non-linear load if the harmonic current injected into the circuit are odd harmonic currents, then the complex waveform produced will have symmetrical resultant waveform. Producing a positive and negative half, identical waveform results in cancelling each other out. However, it is likely that mainly symmetrical waveforms are to be expected as the majority of the harmonics are odd number harmonic frequencies of the third and fifth and so on. Even number harmonic currents are only common if half wave rectification is used. However, this is not common nowadays due to the wide availability of electronic components in the world market at relatively low cost to all consumers. Another measurement to do is to identify the supply feeding the programmable logical controller laboratory where the majority of the load is information technology equipment, resulting in a non-linear load. From this measurement it is expected that a large third harmonic current will be evident and gradually the odd harmonic currents will reduce as the harmonic frequencies increase. Particular attention will be paid to the neutral current and to consider calculating the current rating of the cable installed to see if it is close to or beyond its current carrying capacity due to harmonics. This will cross reference ECTI rules, IEC Standard 60364-5-52 and Chapman’s paper whereby the neutral must be sized accordingly so that it will not be overloaded by harmonic currents. If this was the case the insulation of the cables would breakdown, resulting in the installation being reduced and potentially destroyed, as a result of the overloading current and the heating effect. This would affect the security of supply and the cable having to be eventually replaced with the added potential fire risk. It is the case if Harmonic currents are excessive a circuit breaker monitoring the neutral current can interrupt the three phase currents before damage to the cable can occur. The first measurement to conduct is to connect a filament lamp load and measure the phase and neutral currents at balanced, with a true RMS and average RMS amp meters where usually they should read the same values of current with the two different type meters. The reason to come to this consideration is because their load is linear, as the current and voltage waveforms will be sinusoidal and power factor will be at unity. The second measurement will have a non-linear load consisting of a number of compact fluorescent lamps. Again the current of all the three phases and the neutral will be recorded, with the use of a true RMS and average RMS amp meters. In this measurement it is expected to have a greater current than expected due to the nature of the non-linear Harmonic load. Again, this measurement will be measured at balanced conditions. Will the neutral current be three times the phase current? The presumption would be not as much as three times greater as it will be more than the third Harmonic current created by the load. The Harmonics should also be all in the odd range. There also should be inaccuracies between the different types of instruments. A difference of up to 40% between the two readings is anticipated. For all the mentioned measurements the following will also be measured: all the Harmonic currents; power; displacement power factor; power factor; waveforms and total Harmonic distortion with the Fluke Power Quality Analyser 43B.

All measurements will be of considerable interest to gain an understanding of power quality issues, namely security of supply, computer systems locking out and so on. The fourth measurement will look at the supply drawn by a standard lap-top computer containing a rechargeable battery. Again, this is very common electrical appliance which contains a switch mode power supply, which causes a non-linear load, thus creating harmonics circulating currents in the supply system. The fifth measurement will be a filament lamp controlled by an electronic dimmer, because the filament lamp is being controlled by an electronic dimmer it will be a non-linear load producing several Harmonic currents, but the load is effectively isolated from the supply system. This is a scenario that can be used to analyse the effects of a passive parallel harmonic filter. This scenario has been selected by Stefan Fassbinder of the Leonardo power quality initiative to show how we can tune a passive filter circuit so that the harmonic currents will have a short circuit path in which they can circulate and dissipate. Fassbinder states that the filter reduces THD from 61% to 37% with a 100 watt load and is sufficient enough for a functioning system (Fassbinder, 2003). This is one of the scenarios we must consider if we want to reduce and contain the harmonic currents within the installation producing them. It is also one of the least expensive methods the parallel passive connected filters. The sixth and final demonstration will be the dimmed filament lamp with a tuned passive filter connected in parallel across the load, the same as Fassbinder designed, and will measure and quantify the Harmonic currents before the filter is connected and then the correct and passive filter will be sized up and compare the harmonic currents, THD, and waveforms. If the tuning of the filter is correct, the filter will create a low impedance path for the harmonic current to circulate and contain within. This effectively should also assist in demonstrating how to correct some of the more harmful harmonics. The filter will correct the third and fifth Harmonic i.e. 150 Hertz and 250 Hertz. This is similar to the filter demonstrated in the paper, Passive Filters by Stefan Fassbinder.

Results and Discussion.

Background Harmonics

Figures 5 and 6 show a bar graph looking at the currents that exist when a harmonic analyser is connected solely to a 230v supply, and not connected to a load. The currents that exist are extremely small, in the range of 4 Milliamps and are leakage currents. These exist at various harmonic frequencies. Figure 5 show clearly the 3rd, 6th and 34th harmonic. Figure 6 shows the DC, 3rd, 11th and 36th and 46th harmonics. As stated in the BISRA guide there can be background harmonic levels which can occur. They originate in neighbouring buildings or most likely in this case, are inherited from other circuits in the building where the measurements are being taken.

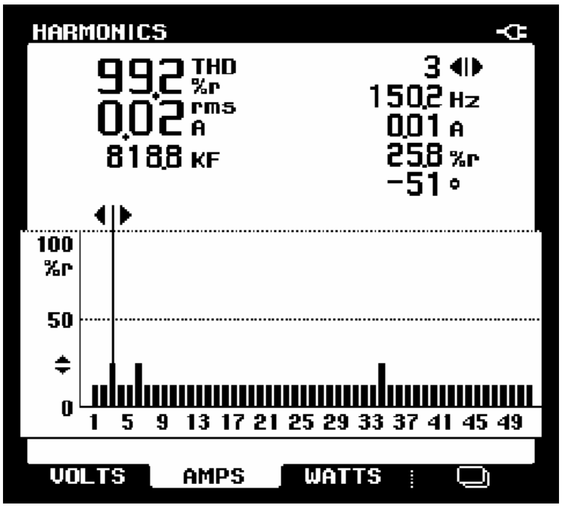


Figure 5. Show the 3rd, 6th and 34th Harmonic at 0.01A

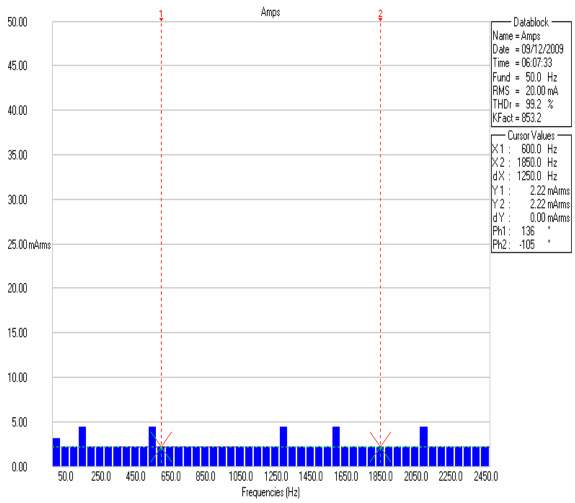


Figure 6. DC, 3rd, 11th and 36th and 46 th Harmonic.

Linear Load Measurement

Figure 7 shows what was displayed from the fluke power analyser 43B instrument connected to a linear load of 5 number 40 watt 230 volt filament lamps. The bar graph measurement shows the fundamental current and the harmonic current up to the 50th. We can see the cursor is placed over the 1st current i.e. the fundamental at 50 Hz. The measurement of 0.82 Amps is the true RMS fundamental current. The reading of 0.81 Amps is the average RMS current at the frequency of the fundamental current of 50 Hz. There are no harmonic currents existing due to the type of load, the total harmonic distortion is virtually zero and the K-factor value is also zero.

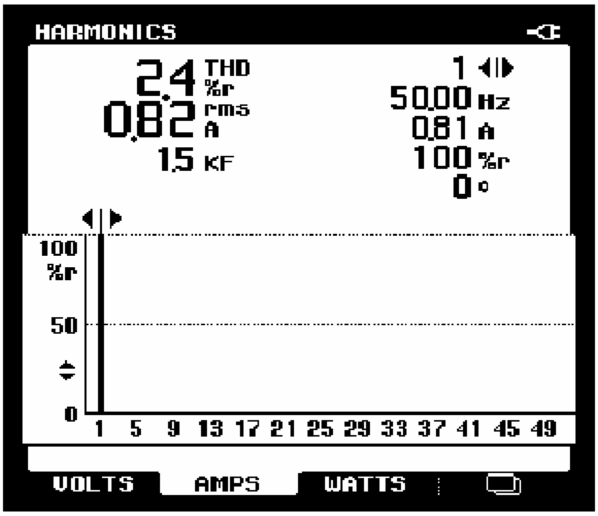


Figure 7. Llinear load of 230 Volt filament lamps

Figures 8 to 9 show the current and the voltage sinusoidal waveforms for a filament lamp, the RMS voltage value of 228 Volt, a fundamental current of 0.79 Amps. Note that the current and the voltage are in phase with each other, therefore the power factor is unity. Also the current waveform is proportional to the shape of the voltage waveform and therefore a linear load. No harmonic current or voltage exists. The sinusoidal waveform and bar graph charts were the same on the phase and on the neutral conductor. No harmonic voltages were present and the only voltage evident was the fundamental voltage.

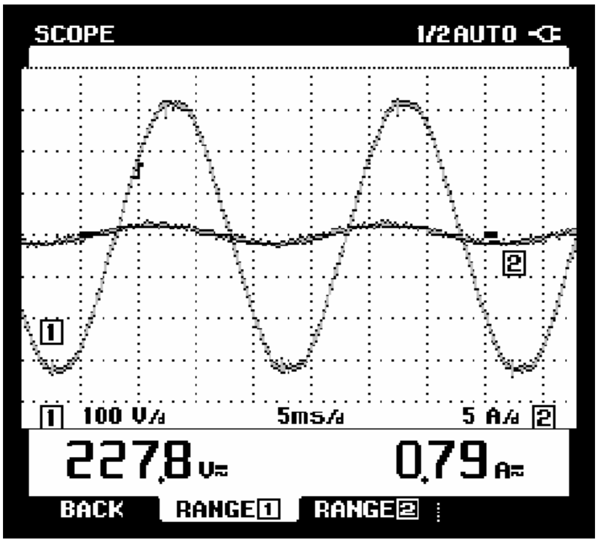


Figure 8. Voltage and current sinusoidal waveform.

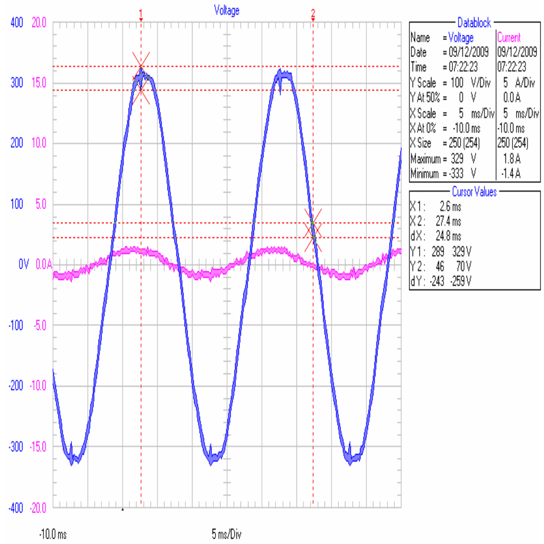


Figure 9. Sinusoidal waveform for a linear load

Non Linear Load Measurement

Figure 10 shows the fundamental current and the harmonic currents produced by two 18 Watt compact florescent lamps (CFL). The true RMS current is 0.22A and the average RMS current is 0.16A, the harmonic distortion is considerable at 70.4% and the K Factor is also considerable at 2.48. The third harmonic i.e. 150 Hz measuring 0.11 Amps, the 5th harmonic is 0.06 Amps, the 7th measuring 0.05 Amps, the 9th 0.04 Amps, the 11th 0.02 Amps and the 13th at 0.01 Amps.

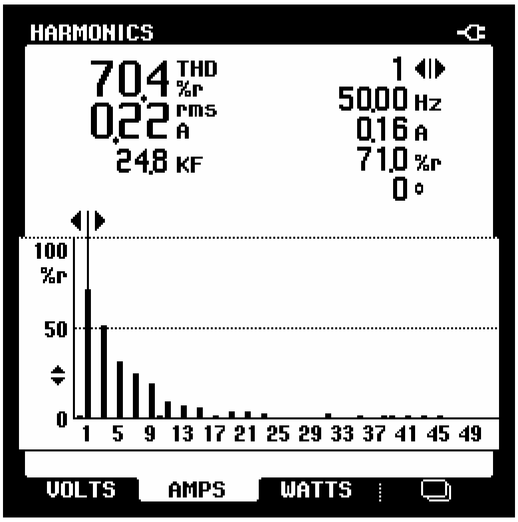


Figure 10 CFL Fundamental and harmonic currents

Now, if we look at the same loads, voltage and current in Figures 11 and 12, we can see the sinusoidal waveforms of the voltage and the non-sinusoidal waveform of the current. This is an example of a non-linear load, where current is taken by the load on a part basis. Unlike the current waveform shown in Figures 8 and 9 for the linear load, where the voltage and current have very similar sinusoidal waveforms, with the exception of the magnitude.

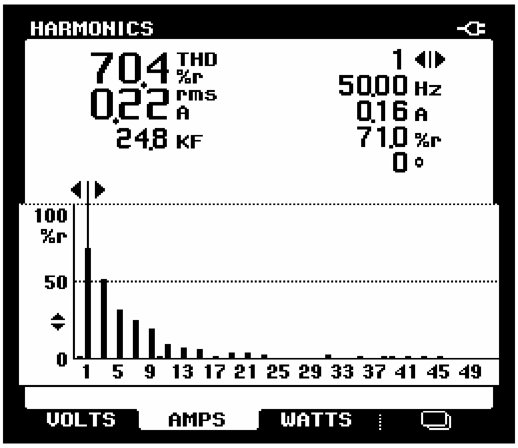


Figure 11. CFL Non Linear load current bar graph.

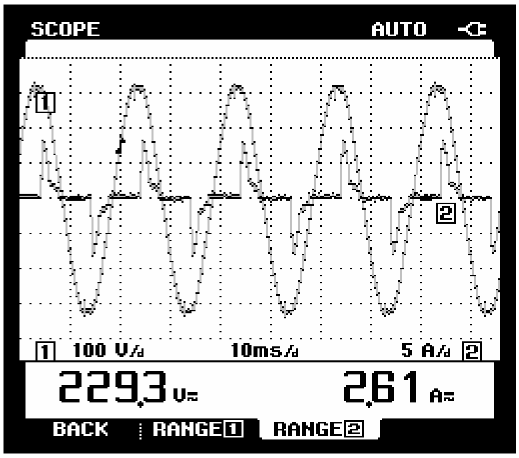


Figure 12. CFL Non Linear current waveform

Linear Load 3 Phase Measurement

The next measurement compares a 40 Watt filament lamp with a linear load and a 40 Watt compact florescent lamp load with a non-linear load. At balanced conditions over a 3 phase 400 Volt supply. The main reason for this measurement is to examine the neutral current. Figure 13 - 14 shows the fundamental and harmonic currents in the neutral conductor. As expected they were all zero for the linear load.

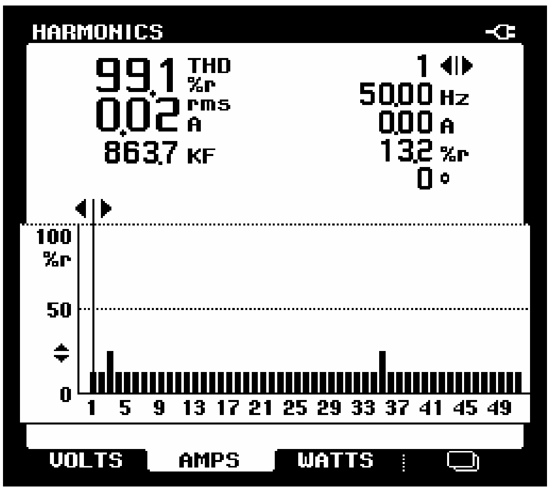


Figure 13. Neutral current in a balanced non linear load.

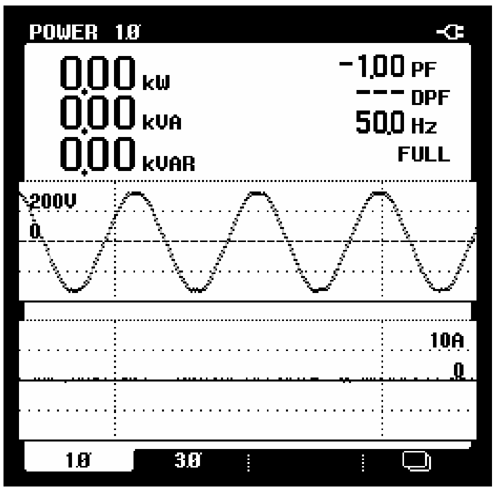


Figure 14. Phase currents in L1 non linear load.

Non Linear 3 Phase Measurement

The more interesting reading was that of the compact florescent lamps, the non-linear load. Figure 13 shows the fundamental and harmonic currents for the first phase L1, consisting of the numerous harmonic currents. Figures 15 to 18 show the harmonic current's measurements in the neutral conductor at balanced conditions connected to a 3 phase 400 Volt supply with a 20 Watt CFL lamp per phase. Note, that there is no fundamental current in the neutral, but a considerable harmonic current. It is evident that the fundamental currents cancel each other out. However, not all the harmonic currents cancel each other out. The third harmonic current is the largest in magnitude and has quite considerable effects on the current in the neutral conductor. So, at balance for a non-linear load, only some of the harmonic currents cancel each other out namely the 5th and the 7th harmonic. Where the 3rd and the 9th do not cancel out, but actually add together resulting in a considerable harmonic current in the neutral conductor.

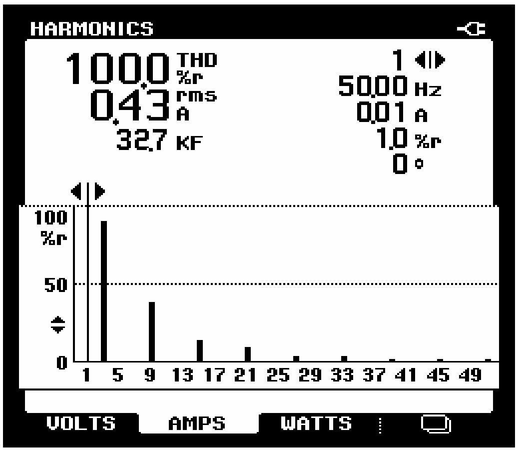


Figure 15. 3phase balanced load no fundamental current

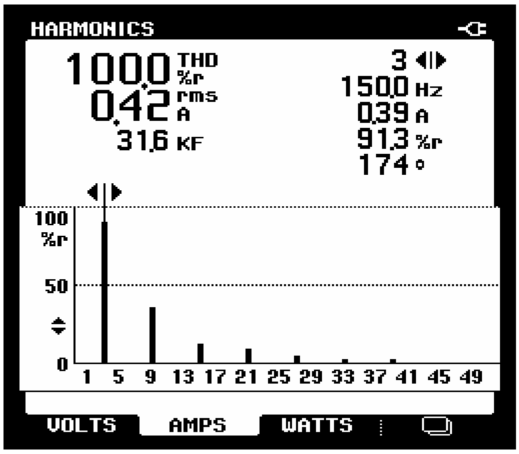


Figure 16. 3phase balanced measuring the 3rd harmonic

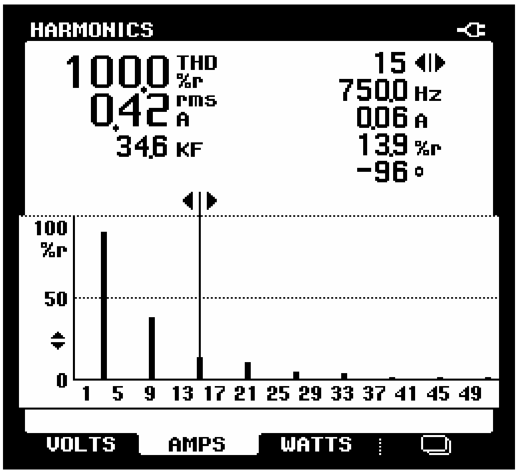


Figure 17. 3 phase balanced load showing 9th harmonic current.

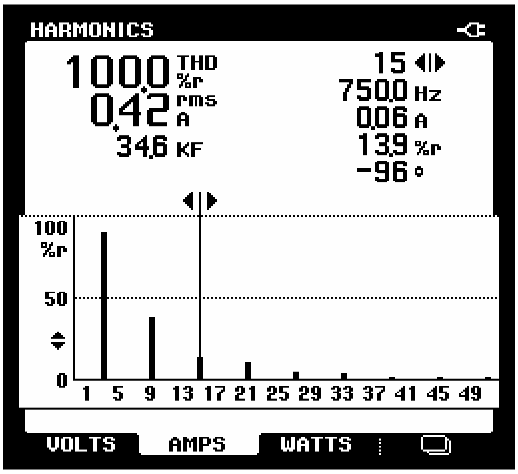


Figure 18. 3 phase load showing 15th harmonic current.

Average and True RMS Measurement

This can also be verified by the recordings in Figure 18 which shows the fluke 43B analyser, on the right hand side, measuring the neutral current and supported by the middle rapid 716 multi meter which measured the true RMS current at 0.646A. The average RMS meter, which is the Rapid 328 DMM meter on the left hand side, is shown measuring a current of 0.38 Amps.

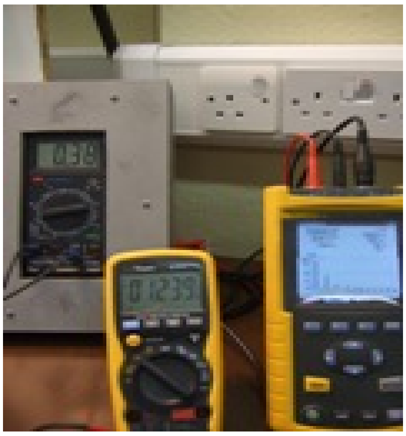


Figure 19. Neutral Current measurement for a 3 phase balanced CFL load

Figure 20. Neutral and phase current measurement for a 3 phase balanced CFL load

Figure 19 shows the six balanced CFL lamps over 400 Volt, 3 phase supply on the left hand side the gray average RMS amp meter model 328 DMM meter measuring the line current L1 at 0.15A , 2nd meter from the left hand side is the true RMS amp meter measuring current in phase L1 at 0.255A. We can clearly see the neutral currents are 2.5 times more than the phase current.

The results of the next measurement can be seen in Figure 20 which shows the phase current supplying 36 Watts of a non-linear load. The left hand side grey meter, the Rapid 329 D meter, measures the current by calculating the average RMS current reading of 0.15 Amps. Whilst the right hand side, yellow edged meter, the Rapid 716 Multi Meter, measures the phase currents true RMS value at 0.257 Amps. West reported at an accuracy of up to 40% of a difference between the two types of meters can exist in a circuit feeding non-linear loads (West, 2001). With these values displayed the inaccuracy measurement is 41.63%, remembering that there would also be slight calibration errors between the two meters.

Figure 21. Phase current measurement with a true and a average RMS meters

Transformer Load Temperature Test

The next measurement examines the temperature effects on a transformer with both linear and non-linear loads. Over the period of one hour, a 2 KVA single phase transformer with temperature thermocouples located as follows: one on the core; one in the secondary windings; the third on the primary windings; and the fourth measuring the room temperature. For each test the transformer had to supply a load of 200 Watts and a second load of 2000 Watts. The results are shown in Table 2. By analysing the 200 Watt test it is evident that there was only a slight difference in temperature between the two comparisons and when adjusted for the room temperature there was little difference in temperature. In fact all temperatures were within 0.5 degrees Celsius of a difference. This test was inconclusive as the literature had indicated that due to a non linear load the core temperature should increase as it causes greater losses in the transformer.

Figure 22 shows the measurement of the 200 Watt load, the silver grey transformer on right hand side of the picture being monitored by the Comark temperature instrument in front of the transformer. Figure 23 shows a reading of the room temperature at 21 degrees Celsius. In consideration for the 200W test the load on the transformer was only 10% of its full load value and temperature monitoring at this low value would probably indicate nothing. However, also during the measurement I took readings of the primary and secondary powers and did find the primary power measured for the linear load was 220 watts. However, the primary power measured for the non-linear load was 240 watts. Meaning the non-linear load still required 20 watts more to supply this type of load, indicating a increased in power consumption of 8.3%.

Figure 22. 200W transformer test

Figure 23. Transformer temperature monitoring

This lead to a further test to fully load the transformer. The results are shown in Table 2-4 below. This test was inclusive as the temperature recorded was far higher supplying the linear load. Some possible reasons for this result were the non linear load test was done in a draughty switch room which assisted cooling of the transformer. The harmonic load was not excessive to such an extent as to affect the losses in the transformer. The measurements can be seen in Figures 24 to 27.

	Non Linear Load			Linear Load		
Ambient Temp °C	18	18	20	22	20	22.5
Primary Temp °C	21	32	42	20	22.5	22.5
Secondary Temp °C	21	32.5	41	21	40	49
Core Temp °C	21	22.5	29	20.5	33	40
Time	15.45	16.15	16.45	16.45	17.15	17.45

Table 2. Transformer temperature test 2 KW load

	Non Linear Load			Linear Load		
Ambient Temp °C	20	20.5	21	21	21.5	20
Primary Temp °C	20	20.5	22.5	20.5	22	21.5
Secondary Temp °C	20	21.5	22	20.5	22.5	22.5
Core Temp °C	20	23.5	25	20.5	25	26
Time	19.35	20.05	20.35	18.17	18.47	19.17

Table 3. Transformer temperature test 200 W load

Ambient Temp °C	21	20
Primary Temp °C	22.5	24
Secondary Temp°C	22	24
Core Temp °C	25	27
Time	20.37	21.07

Table 4. Transformer temperature test 400 W linear load and non linear

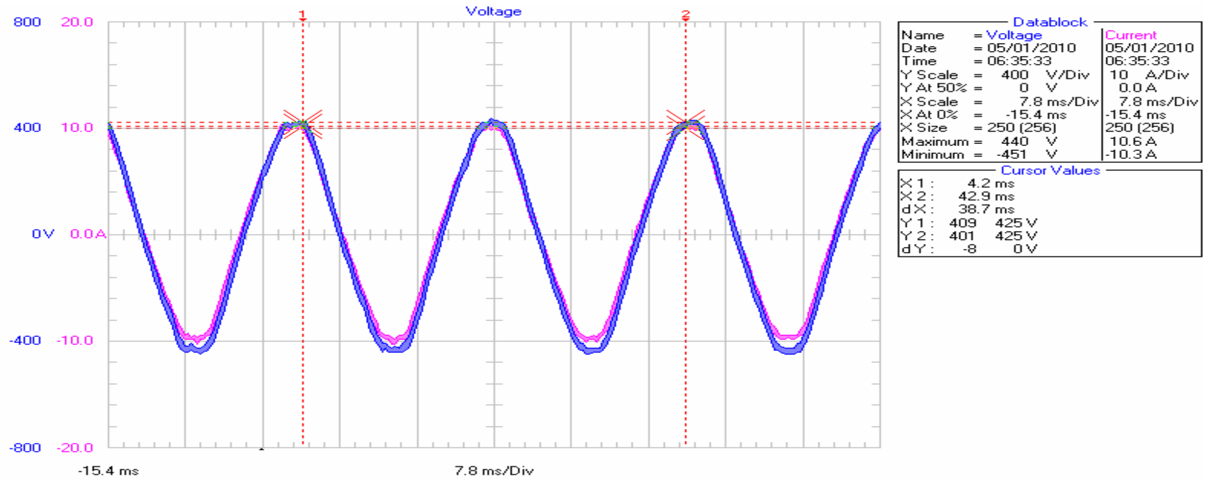


Figure 24. Linear load Transformer 2 KW test, voltage and current waveforms

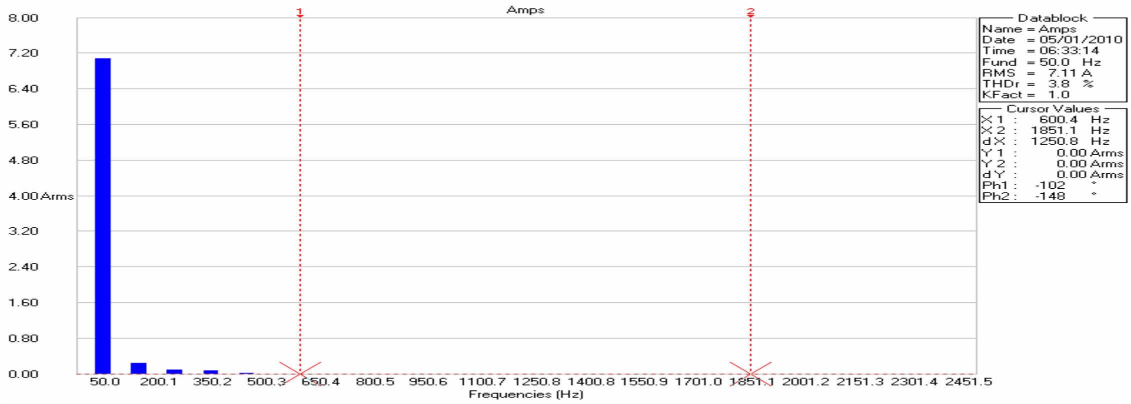


Figure 25. Linear load Transformer 2 KW test, current bar chart

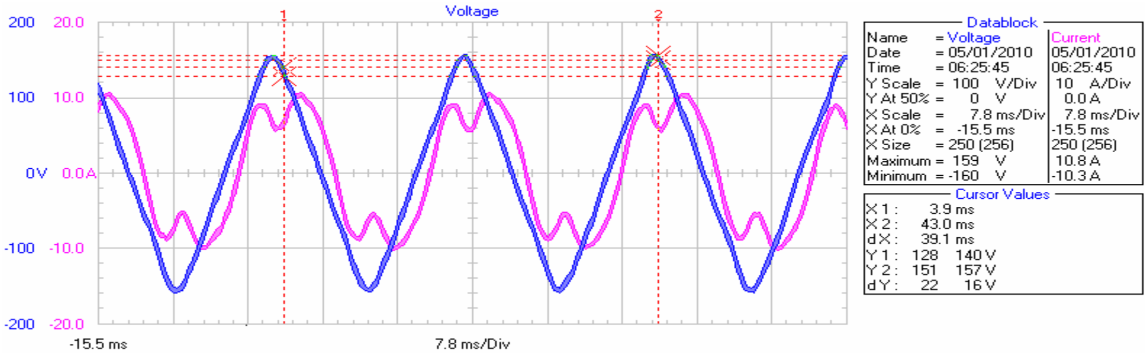


Figure 26. Non linear load Transformer 2 KW test, voltage and current waveforms

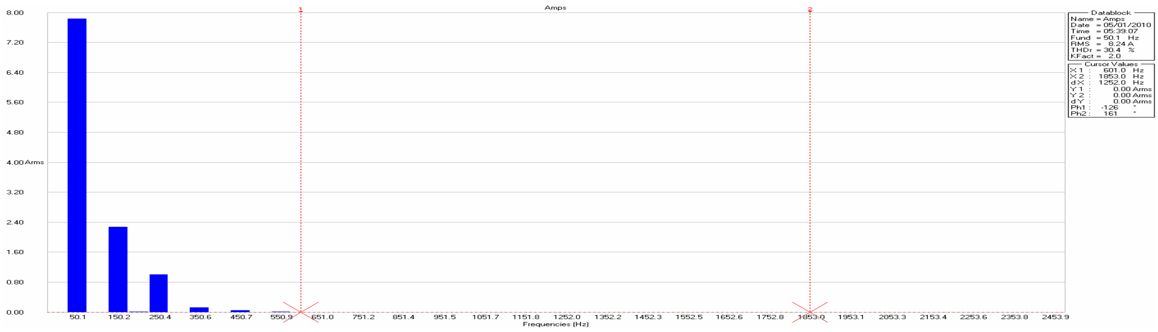


Figure 27. Non linear load Transformer 2 KW test, current bar chart

Laptop Measurement

Figure 28 shows a measurement of a typical laptop computer, showing fundamental, 3rd and 5th harmonic currents. Figure 29 shows the power consumed by the laptop showing power factors, the voltage and current waveforms. In relation to the power quality it is common to measure the power factor (PF) and displacement power factor (DPF).

Displacement power factor is a ratio, the phase angle between the fundamental current and the fundamental voltage which measures 0.9. The second power factor (PF), is the true ratio between voltage and current and the power with all the harmonics factored in. The reading for the PF was 0.59. Note, that the greater the difference between the DPF and the PF the greater the harmonic distortion. Viewing Figure 34 we can actually analyse and measure all the harmonic currents that are generated by the laptop computer power supply.

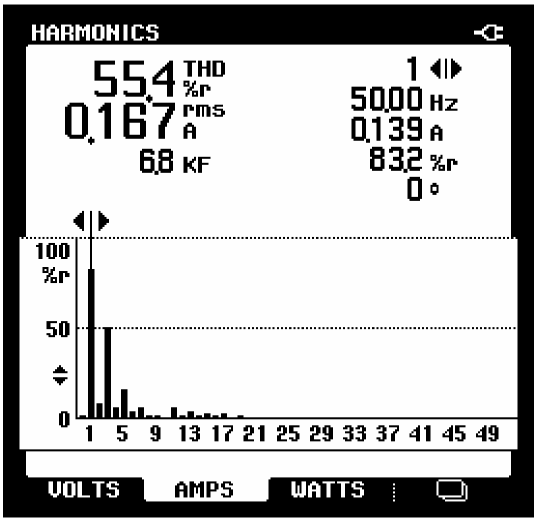


Figure 28. Laptop current bar graph

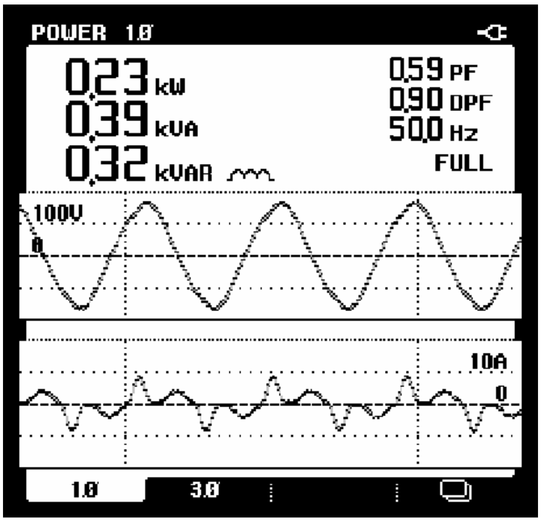


Figure 29. Laptop voltage and current waveforms

Discussion of Results

It should be clearly seen that Chapman and West are correct in their papers. An inaccuracy between readings showed a difference of 41.6%. This is due to the fact that the filament lamps are a linear load and the current is in the sinusoidal sine wave. Whereas the compact fluorescent lamp load is non-linear, having a current wave form which is distorted and clearly non-sinusoidal resulting in the accurate measurement of current being from the true RMS meter. This clearly demonstrates that harmonics exist in a circuit and must be measured and quantified by means of a harmonic analyser type instrument.

Measurement of a non linear Information Technology Load

Another interesting measurement, which is beneficial to our knowledge and understanding of harmonics and their effects, was the examination and review of practical everyday loads, this measurement relates to Information Technology equipment, specifically personal computers. The practical measurement available was a programmable logic controller (PLC) laboratory. This lab consists of: seventeen programmable logic controllers; seventeen personal computers, including monitors, human machine interfaces (HMI) servers and monitors associated with that equipment. All the equipment is fed from separate switch mode power supplies over a three phases and neutral 400 Volt supply. The measurement was taken at the main distribution board and at the point of common coupling. The following measurements were taken on the neutral see figures below 30 -33.

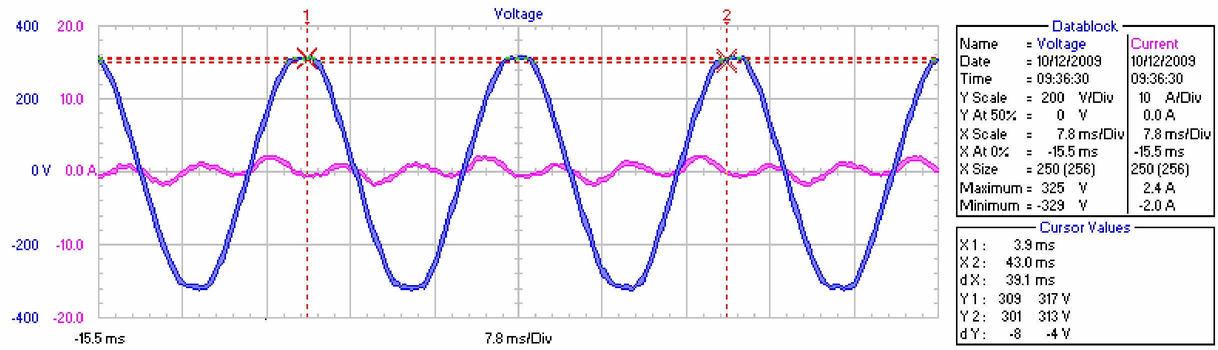


Figure 30. PLC neutral voltage and current waveforms

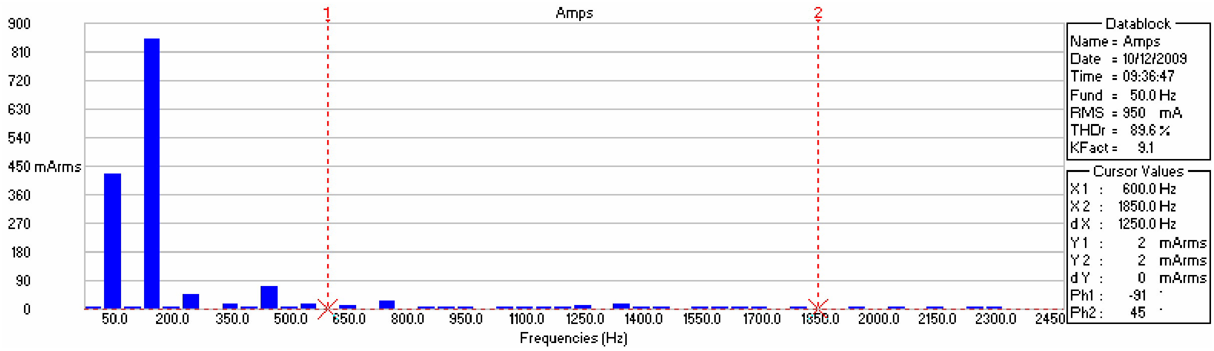


Figure 31. PLC neutral current bar chart

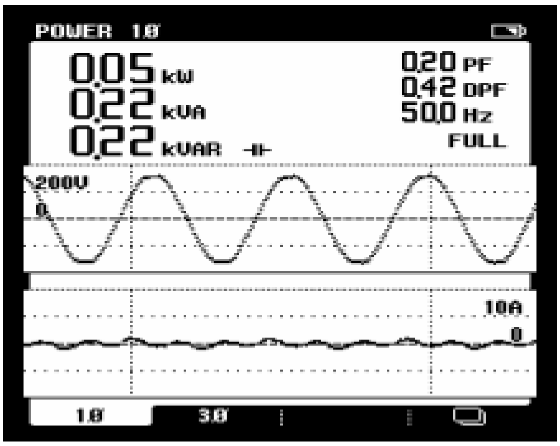


Figure 32. PLC Lab Power measurements

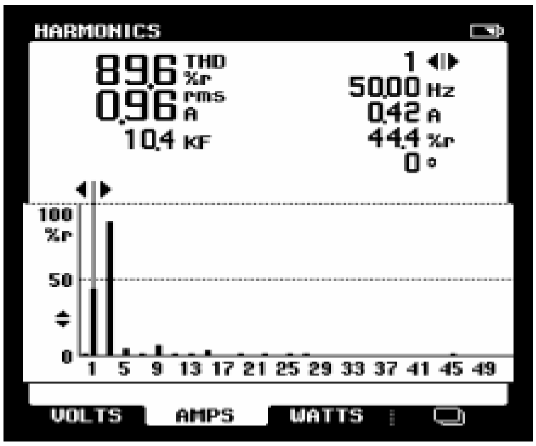


Figure 33. PLC fundamental current measurement

The next measurements taken are shown in figures 34 - 39 the three phases containing harmonic currents. The phases are not at balance and the neutral contains a fundamental current and contains predominantly the third harmonic current value, in fact 100% more than the fundamentals current. All the waveform diagrams show a far from sinusoidal current waveform due to the harmonic distortion considerable differences between the displacement power factor and the power factor indicating harmonic distortion especially on phase L1. Interesting the overall frequency of the neutral current is at 150 Hz the frequency of the predominate harmonic current as seen and measured in figure 24 total harmonic distortion for all the phases around 70%. However, the total harmonic distortion for the neutral was 90%. The K factor for L2, L3 and the neutral were around 10 and L1 it was 15.7 very high values.

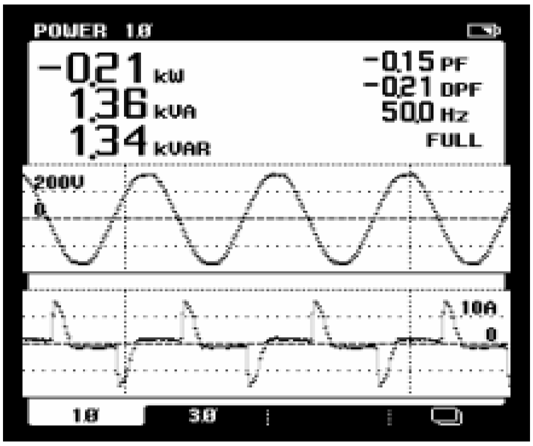


Figure 34. PLC Lab phase L1 power and voltage waveforms

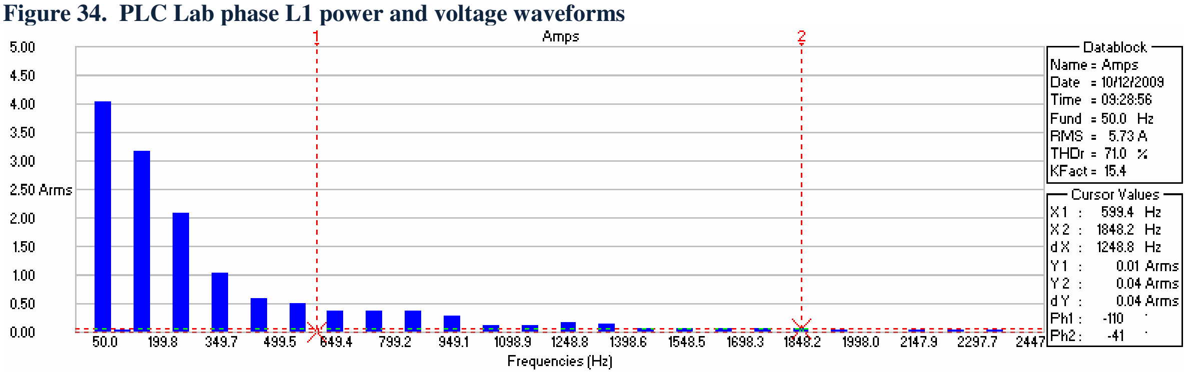


Figure 35. PLC lab phase L1 current bar graph

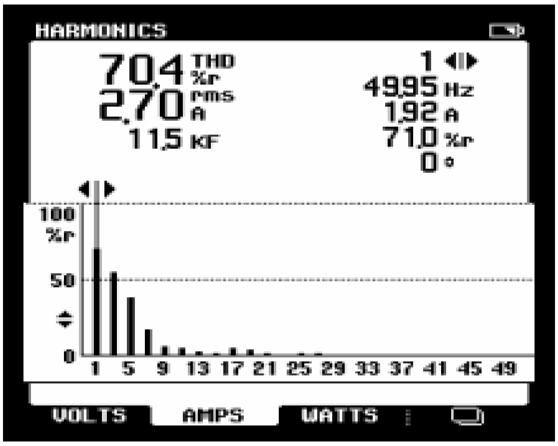


Figure 36. PLC lab phase L2 current bar graph

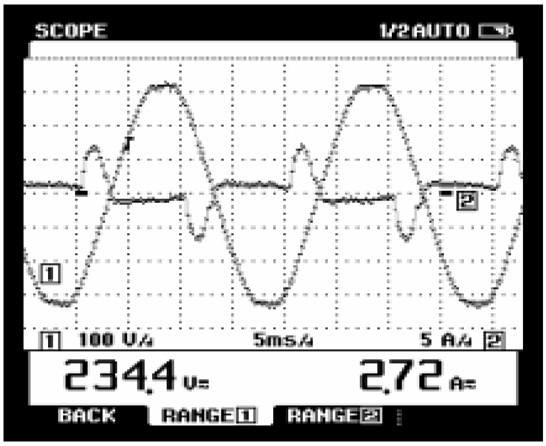


Figure 37. PLC phase L2 voltage and current waveform

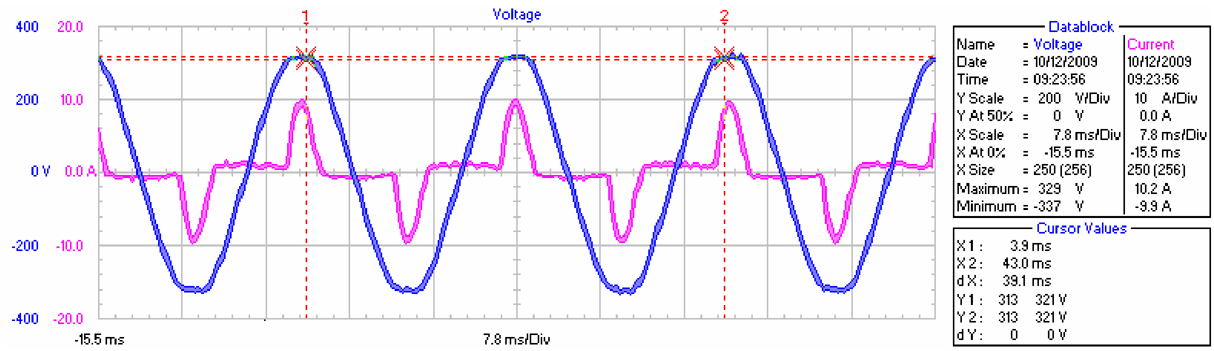


Figure 38. PLC phase L3 sinusoidal Voltage and distorted current waveform

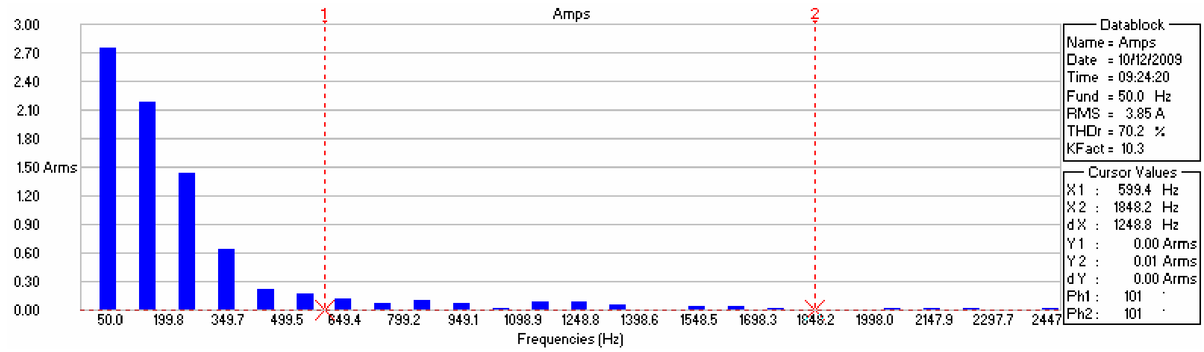


Figure 39. PLC phase L3 current bar graph

Harmonic analyses at the Point of Common Coupling

The next measurement is taken again at the main intake point, the point of common coupling at the main distribution board of the Church Lane building supplying the entire building. Readings were taken early evening with the building at part capacity, Figures 40 - 43 showed the bar graphs and waveforms for phases L1. Harmonic current level was not so high, the fundamental current at 29A, the fifth harmonic current is 3.2A which is greater than the third harmonic current at 1.5A.The voltage waveform is distorted and slight flattening of the sinusoidal voltage waveform can be seen this is a typical problem caused by harmonics and causes power quality problems at great expense in the region of €100, s of billion of euro to our economy, the power factor is also poor and the current is lagging the voltage.

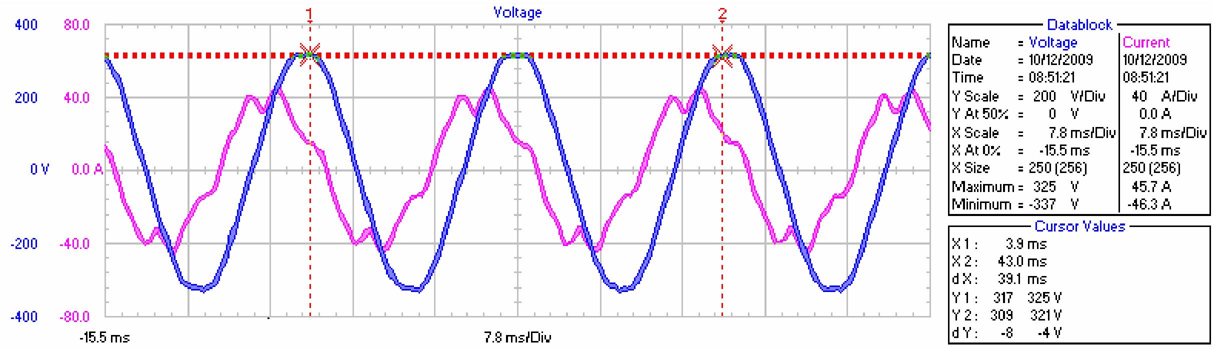


Figure 40. Harmonic and power quality measurement phase L1 at main intake point, point of common Coupling (PCC)

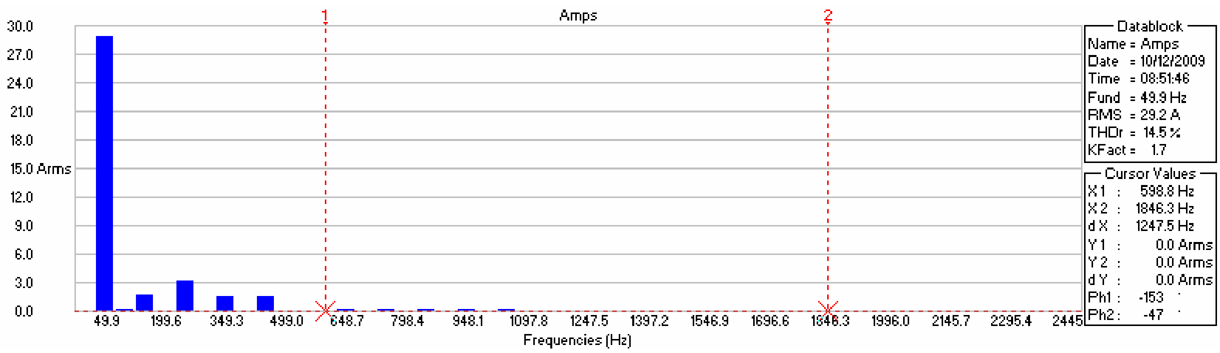
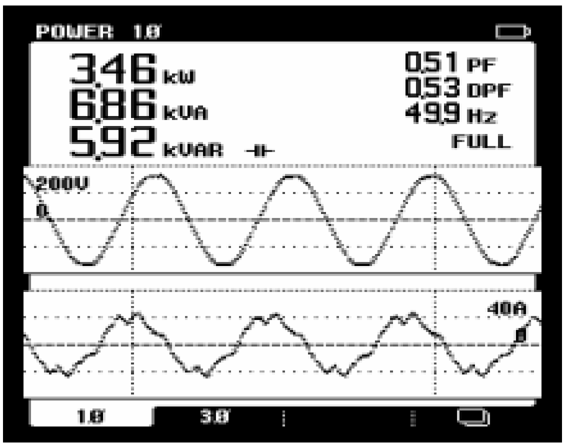


Figure 41. Harmonic and power quality measurement phase L1 current bar graph at PCC



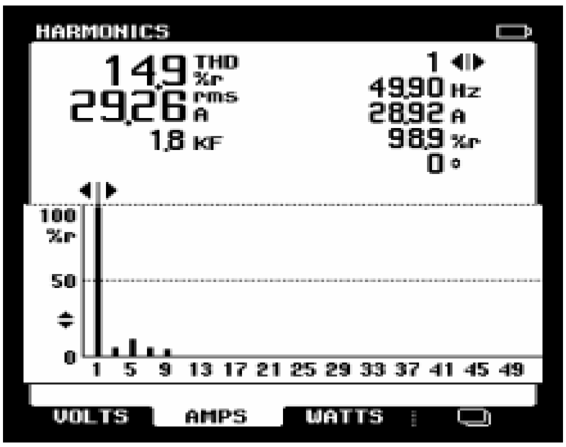


Figure 42. Voltage and current waveforms for phase L1 at PCC

Figure 43. Current bar graph for phase L1 at PCC

Figures 44 to 47 show phases L2, slightly similar to L1, the third harmonic current 3.4A, greater than the fifth at 2.6A and total harmonic distortion at 29%.

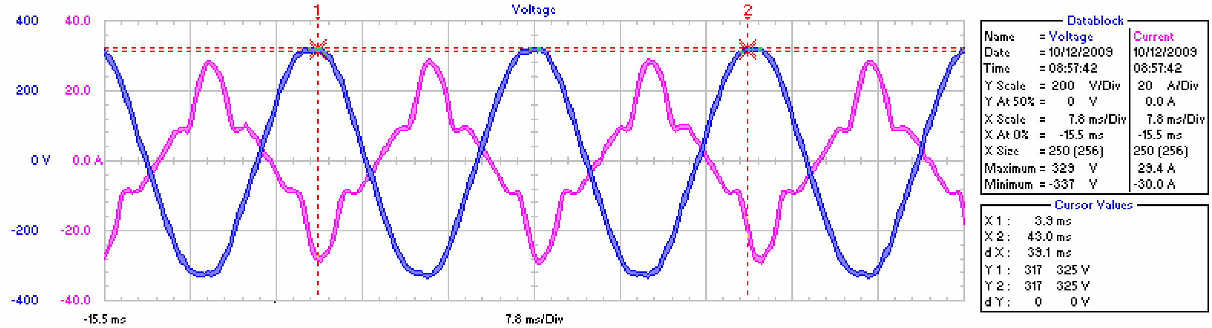


Figure 44. Harmonic and power quality measurement phase L2 at main intake point, point of common coupling (PCC)

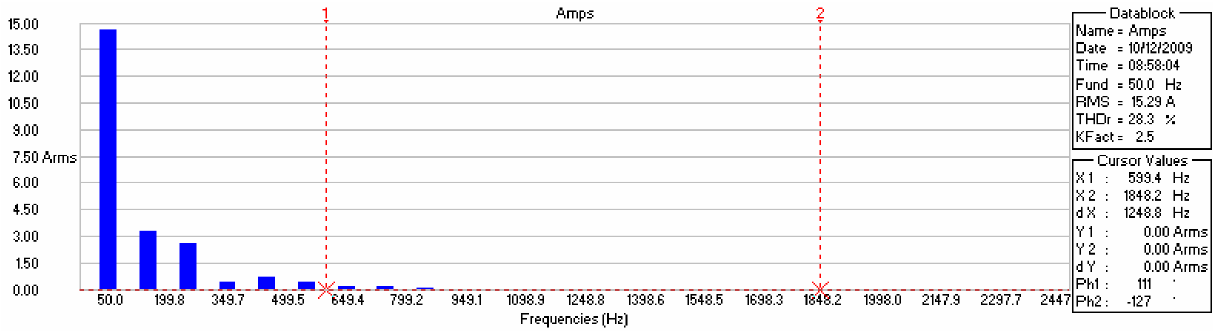


Figure 45. Harmonic and power quality measurement phase L2 current bar graph at PCC

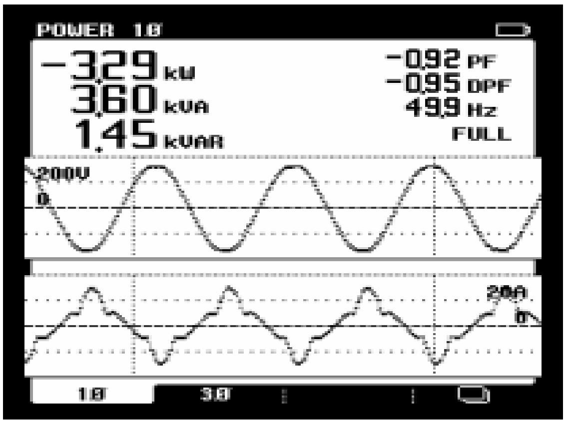


Figure 46. Voltage and current waveforms for phase L2 at PCC

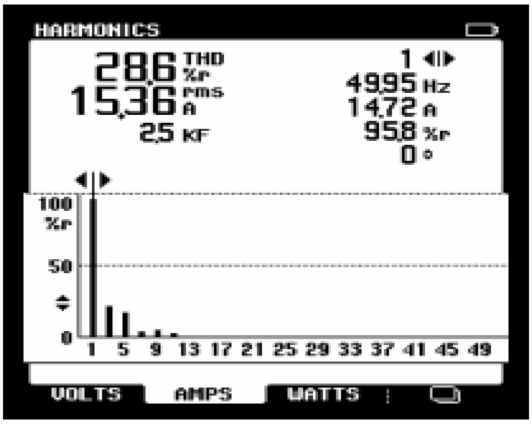


Figure 47. Current bar graph for phase for L2 at PCC

Figures 48 to 51 show phases L3, the phase which has the lowest harmonic distortion and the power factor is poor.

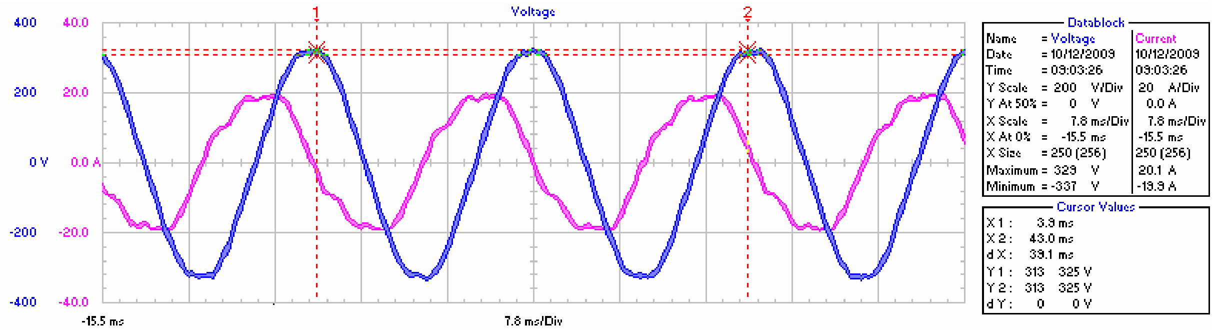


Figure 48. Harmonic and power quality measurement phase L3 at main intake point, point of common coupling (PCC)

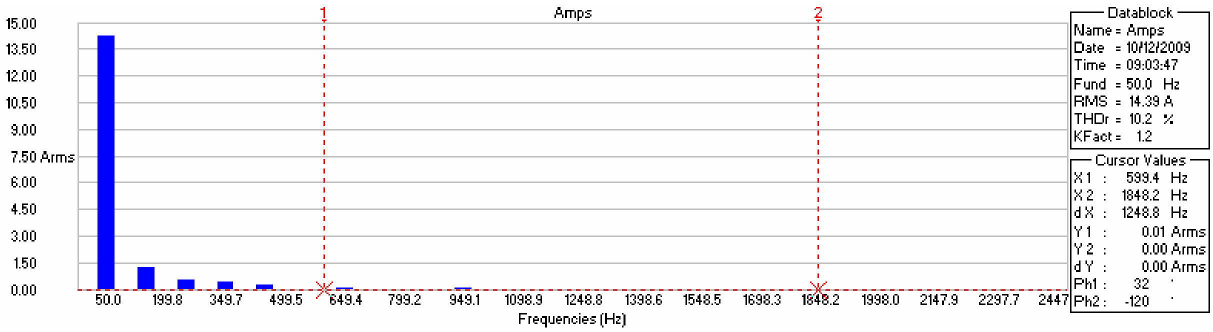
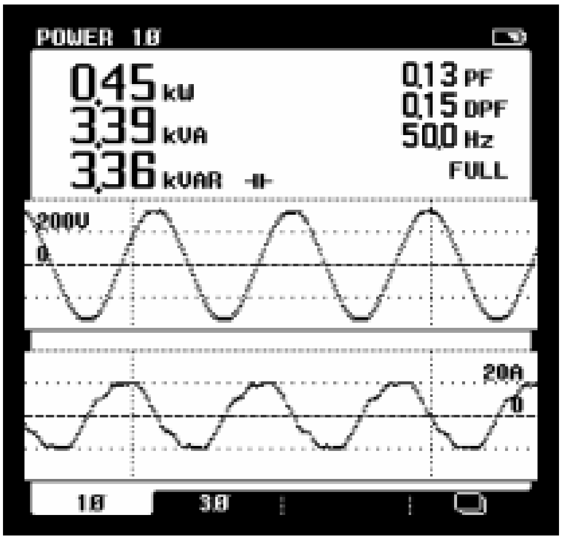


Figure 49. Harmonic and power quality measurement phase L3 current bar graph at PCC



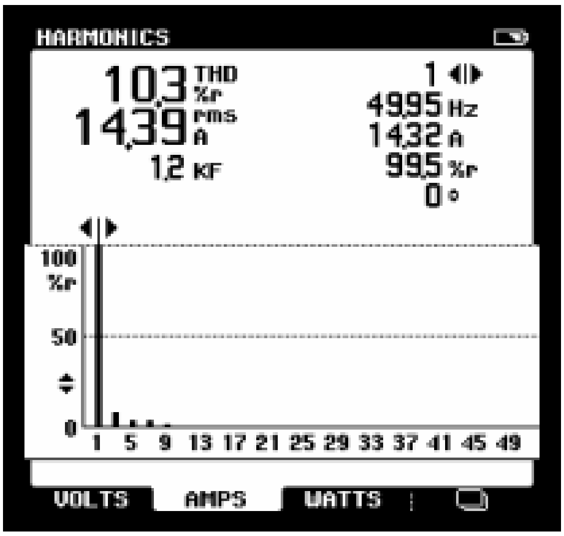


Figure 50. Voltage and current waveforms for phase L3 at PCC

Figure 51. Current bar graph for phase for L3 at PCC

Figures 52 to 55 shows the neutral conductor, the fifth harmonic current 3.3A is the greatest harmonic current here at 27% of the fundamental current. Power factor is at 0.2 and has a well distorted current waveform.

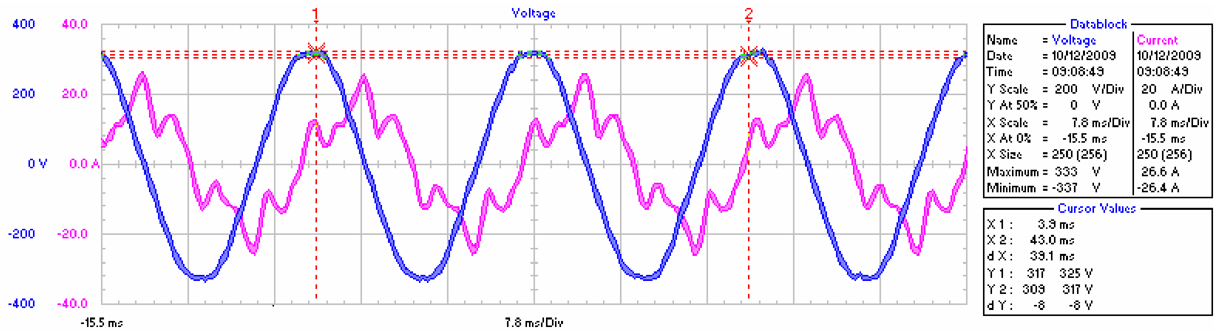


Figure 52. Harmonic and power quality measurement neutral conductor at main intake point, point of common coupling(PCC)

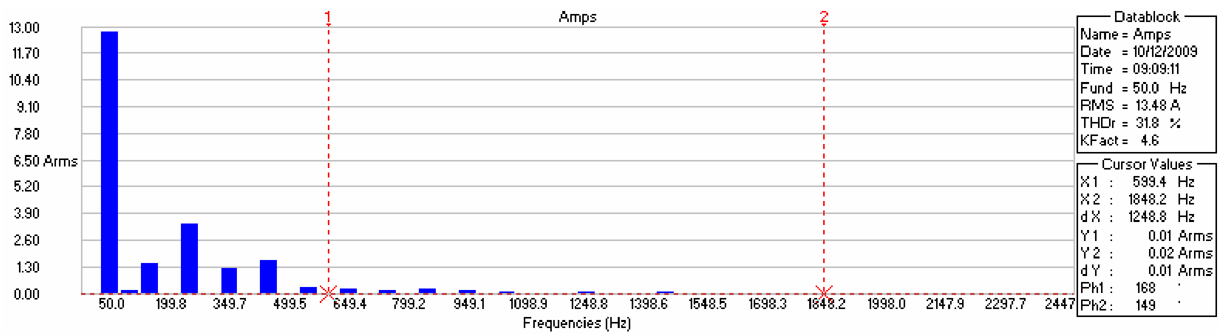


Figure 53. Harmonic and power quality measurement neutral current bar graph at PCC

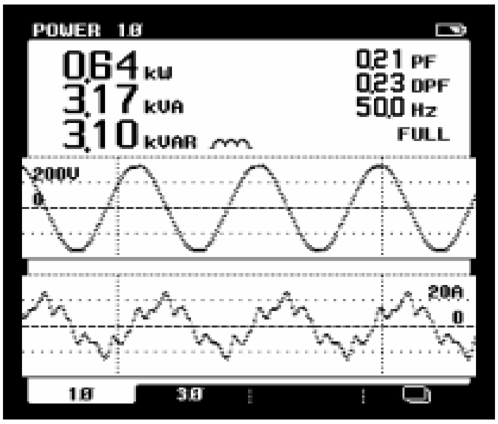


Figure 54. Voltage and current waveforms for neutral conductor at PCC

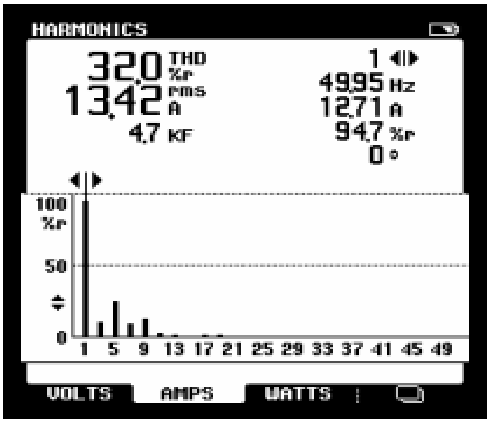


Figure 55. Current bar graph for neutral conductor at PCC

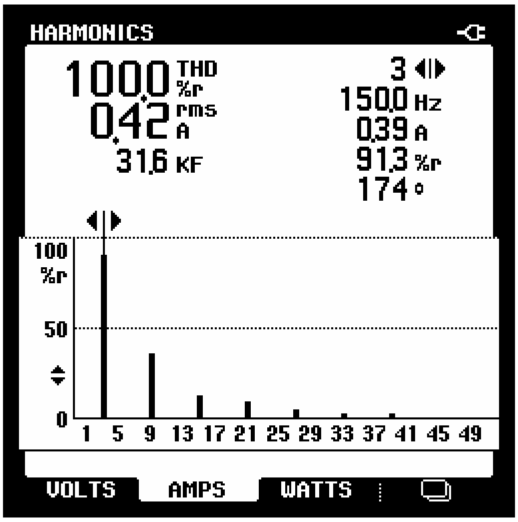
Conclusion

On the basis of the findings up to now, the understanding of alternating current and voltage were of two similar sinusoidal waveforms, not necessarily in phase with each other as the creation of a magnetic field causes the current to lag the voltage. Furthermore, the frequency of the voltage and current was 50 Hz, determined by the generator that produced the electrical energy. Great care is taken in the production of electrical energy to produce the sinusoidal waveform at a frequency of 50 hertz. This ensures a uniform quality of electrical energy to all types of loads, at an accurate frequency. This uniform deliverance of electrical energy runs our electrical machines and upon which our modern way of life is now reliant.

The type of electrical equipment, upon which we are now totally dependent for all aspects of our personal and professional lives, is causing this problem of power quality. The manner in which the non-linear loads consume and demand their electrical energy is causing our sinusoidal waveform of current and voltage to be a much distorted, complex waveform consisting of many currents at different frequencies. When the current and voltage supplying a linear load of a 40 watt filament lamp was examined, the sinusoidal waveform of current and voltage were very similar and the current being drawn by the load was proportional to the voltage. The only voltage and current that existed was that at 50 hertz the fundamental voltage and current waveforms.

Conversely, when a non-linear load of 36 watts that of a compact florescent lamp, was examined and analysed, a very different picture emerged. The fundamental voltage and current was measured at 50 Hertz, but many other currents existed at various other multiple frequencies of the fundamental frequency. All of these were the odd number frequencies. These currents are known and are referred to as harmonic currents and are injected into the supply system by the manner of the load controls and demands its power. In the case of compact florescent lamps, the power supply to the load is controlled electronically. However, throughout this study it is not only electrical power controlled electronically that creates the harmonic currents, they are created by discharge lighting like the fluorescent lights that loaded the transformer on the temperature test. Through this research it has been demonstrated that the majority of all loads are non-linear and that this is very undesirable causing more expense than we could imagine. The power supply of the CFL lamps produced multiple currents at varying odd number frequencies causing the supply sinusoidal waveform to be distorted and un-uniform. The harmonic current circulates around the supplies wiring system and it has also been found that they do not cancel each other out at certain frequencies. This was the next area examined where it was found that with the linear load at balance conditions, the current in the neutral conductor was zero. This is due to each phase being displaced by 120 degrees and the sum of the currents cancelling each other out.

This will occur only in relation to sinusoidal waveforms. This was what was assumed to happen when a load draws a current on a non-linear basis and the wave is complex and not sinusoidal. After conducting an experiment using a compact fluorescent lamp with a 36 Watt load over three phases at 400 Volt supply, connected in a star formation with a neutral conductor. It was found again that the harmonic currents that were produced were odd number harmonics. There are no even harmonics because the full wave rectifier draws the same current on the positive as it does on the negative. Furthermore, the fundamental current was zero, as was the fundamental current on the linear load. However, the third harmonic current measured 0.39A and when the third harmonic current was measured for the same load with a single phase load it measured 0.16A. Therefore the third harmonic current connected to the three phase non-linear load did not cancel out but actually added together. In fact, the measurement is 2.5 times the phase current. As can be seen in Figures 56 - 57, showing the third harmonic current measured in the neutral conductor and Figure 57 showing the phase fundamental current. Also the measurement shows a 9^{th} harmonic current of 0.16A on the neutral conductor and 0.06A on the 15^{th} harmonic. All other harmonic currents, except the Triple N currents cancel each other out. The measurement clearly demonstrates that when supplying a non-linear load the neutral current does not cancel out but actually adds together and this can cause the neutral conductor to be overloaded and the necessity to apply the IEC standards.



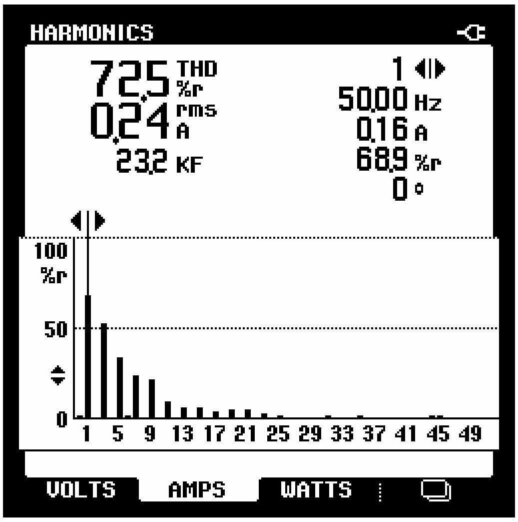


Figure 56.

Figure 57.

Therefore a full understanding of the IEC standards, regarding cable sizing for an electrical installation supplying a predominantly non-linear load, is required. This measurement is further supported by the instruments measuring the Total Harmonic Distortion (THD) which indicated 100%. This is a measure as to the extent of distortion of the waveform for a non linier load Also the power factor of 0.1 and a displacement power factor of 0.80, these types of power factors are also an indication of a non linear load. Commonly, the power factor is derived by true power divided by the voltage, multiplied by the current. This is what is known as the displacement power factor. However, this is not correct for non-linear loads. The power factor for harmonic loads is the displacement power factor's cosine, multiplied by the fundamental current, divided by the current's RMS. The true current's RMS value will be greater than the fundamental current's RMS value; resulting in a power factor of a poorer value this is causing much greater losses. This will necessitate installing larger distribution equipment such as cables and transformers and this further proves harmonics do not provide useful power to the load but increase the electrical power required to supply the load. A question was posed at the introduction do harmonics cause losses and can electrical energy be conserved, the answer is yes by having a better understanding and measurement methods to analyse and quantify harmonics we can save on our losses and improve on our security of the electricity supply.

It is commonly considered that an inductive load causes current to lag voltage but this consideration was only for the fundamental current and voltage. Further consideration is that the harmonic currents that are not cancelled out, this will inevitably cause voltage distortion, which inevitably will affect other equipment which is connected in parallel with the harmonic non-linear load.

The harmonic voltage distortion will be dependent on the current multiplied by the source impedance of the supply network which will be 2 times Π (3.141), multiplied by the frequency, and multiplied by the inductance. This would mean the impedance of the supply, will increase with the increase of the frequency of the harmonic current. This in turn would cause a large distortion of the voltage waveform. The distribution system impedance in any installation is necessary to accurately predict the level of distortion. This distortion would cause malfunction of equipment connected to the supply and the lower the impedance for a electrical network the better the network will be. Also equipment, designed for a sinusoidal waveform, that uses a zero crossover reference point that is more likely to be affected by the harmonics previously shown in figure 4 the distorted current waveform has 6 zero crossover points. Another area of understanding reached was in the area of current measurement. By using two different types of amp meters, firstly the average RMS and secondly the true RMS meter, it was when measuring currents supplying a linear load – the meters displayed the same values. However, when measuring currents supplying a non-linear load, there was an inaccuracy of 41.6% as measured by the true RMS meter. The average RMS reading being was of a lower value and inaccurate. This is as a result of how the meter is designed. The average RMS meter of a more low cost design, is intended to measure a pure sinusoidal waveform which very rarely exists as this study has found. Due to the simple design, it measures the mean value and multiples it by the form factor and displays this reading. However, the true RMS meter, the more expensive and more accurate meter, measures the square of the instantaneous value of the input current averaged over time and displays the square root of the average current. As a conclusion, for greater accuracy, only true RMS meters should be used to measure power electrical systems.

Referencing

Baggini, A. (2007). Power Quality Tutorial. Leonardo Energy.
Chapman. (2001). The Cost of Poor Power Quality. Brussels: Copper DevelopmentAssociation .
Chapman. (2001). Causes and Effects of Harmonics. Brussels: Copper Development Association.
CIGRE. (2001). Technical report, CIGRE, 2001. PARIS: CIGRE.
Copper Development Association. (2000). Harmonics, Transformers and K-Factors. London: Copper Development Association.
Desmet&Beggin. (2003). Neutral Sizing in Harmonic Rich Installations.
Desmet, D. L. (2009). Selection and Rating of Transformers.
ECTI. (2009). The Fourth Edition of the Irish National Wiring Rules ET101 .
Eurelectric. (2002). Power quality in european electricity supply networks { 1st edition. Technical report,.
Eurelectric. (2002). Power quality in european electricity supply networks {1st edition. Technical report,. Eurelectric.
Fassbinder, S. (2003). Passive Filters . Deutsches Kupferinstitut .
International Electrotechnical Commission. (2007). 60364.
International Electrotechnical Commission. (2008). IEC 364-5-52 - Electrical Installations in Buildings.
Keulenae, H. D. (2003). The hidden cost of poor power quality October 31, 2003 by r,.
Keulenaer. (2002). Power Quality Self-assessment Guide. European Copper Institute.
Keulenaer, H. D. (2006). Power Quality Self-assessment Guide. European Copper Institute.
Keulenaer, H. D. (2003). The hidden cost of poor power quality . Leonardo Energy.
Lemcko, D. D. (2009). Selection and Rating of Transformers. Leonardo Energy.
leonardo-energy.org. (2007). European Power Quality Survey.
Martin. (2009). http://www.copper.org/Applications/electrical/pq/issues.html. copper.org.
Pearson, U. (2000). THE BSRIA POWER QUALITY GUIDE.
Power Quality in European Electricity Supply Networks - 2nd edition Network of Experts for Standardisation.
Prof Jan Desmet, &. P. (2003). Neutral Sizing in Harmonic Rich Installations, .
West, K. (2001). True RMS – The Only True Measurement. Leanardo Energy.

Bibliography

IEEE bronze book: energy management
IEEE Std 739-1995.
IEEE recommended practice for energy management in industrial and commercial facilities / sponsor, Energy Systems Committee of the Industrial and Commercial Power Systems Department of the IEEE Industry Applications Society; approved 12 December 1995, IEEE Standards Board; approved 16 July 1996, American National Standards Institute. New York : IEEE Press, c1996.
Power system quality assessment / J. Arrillaga, N.R. Watson, S. ChenChichester : John Wiley & Sons, 2000
Power system harmonic analysis / Jos Arrillaga ... [et al.].
Chichester ; New York : Wiley, c1997
Surviving your dissertation : a comprehensive guide to content and process / Kjell Erik Rudestam, Rae R. Newton. Los Angeles : SAGE Publications, c2007